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INVESTIGATION OF KEVLAR® FABRIC-BASED MATERIALS FOR USE WITH INFLATABLE STRUCTURES

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Prepared by
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16. Abstract

Although tethered balloons have been in use for over a century, the past decade has produced the greatest increase in the sophistication and complexity of these vehicles and considerable related technology has evolved. Recently developed, high-strength materials for hulls, fins and rigging have made a major contribution to improved windward performance. The new DuPont organic fiber, Kevlar, offers further performance gains. Design, manufacture and testing of laminated and coated composite materials incorporating a structural matrix of Kevlar is reported in detail. The practicality of using Kevlar in aerostat materials is demonstrated and data are provided on practical weaves, lamination and coating particulars, rigidity, strength, weight, elastic coefficients, abrasion resistance, crease effects, peel strength, blocking tendencies, helium permeability, and fabrication techniques. Properties of the Kevlar-based materials are compared with conventional Dacron -reinforced counterparts. A comprehensive test and qualification program is discussed and considerable quantitative biaxial tensile and shear test data are provided. The investigation shows that single-ply laminates of Kevlar and plastic films offer significant strength-to-weight improvements, are less permeable than two-ply coated materials, but have a lower flex life. Creasing causesa significant loss in strength for Kevlar laminates. Further research is proposed to reduce the inherent rigidity of the experimental laminate material. Multiaxial textile constructions of Kevlar such as triaxial weaves or parallel, nonwoven yarn arrays laminated to film gas barriers appear to be potential fabrication techniques of considerable merit.

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FOREWORD

This report was prepared by personnel of Sheldahl, Northfield, Minnesota, under NASA Contracts NAS1-11694 and NAS1-12701 and is based upon work performed by the contractor between June 1972 and June 1975. The work was directed and monitored by the NASA Langley Research Center under the technical direction of Mr. V. L. Alley, Jr., of the Directorate for Engineering and Operations and Mr. Austin McHatton, the Technical Representative of the Contracting Offices, Systems Engineering Division. Funds for this research were provided NASA by the Advanced Research Planning Agency (ARPA) of the Department of Defense.

Certain commercial equipment, special equipment and materials are identified in this report in order to adequately specify the environmental procedures. In no case does such identification imply recommendation or endorsement of the product by NASA, nor does it imply that the equipment or materials are necessarily the best or the only materials available for the purpose.

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INVESTIGATION OF KEVLAR® FABRIC-BASED MATERIALS FOR USE WITH INFLATABLE STRUCTURES

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ABSTRACT

Although tethered balloons have been in use for over a century, the past decade has produced the greatest increase in the sophistication and complexity of these vehicles and considerable related technology has evolved. Recently developed, high-strength materials for hulls, fins and rigging have made a major contribution to improved windward performance. The new DuPont organic fiber, Kevlar®, offers further performance gains. Design, manufacture and testing of laminated and coated composite materials incorporating a structural matrix of Kevlar is reported in detail. The practicality of using Kevlar in aerostat materials is demonstrated and data are provided on practical weaves, lamination and coating particulars, rigidity, strength, weight, elastic coefficients, abrasion resistance, crease effects, peel strength, blocking tendencies, helium permeability, and fabrication techniques. Properties of the Kevlar-based materials are compared with conventional Dacron®-reinforced counterparts. A comprehensive test and qualification program is discussed and considerable quantitative biaxial tensile and shear test data are provided. The investigation shows that single-ply laminates of Kevlar and plastic films offer significant strength-to-weight improvements, are less permeable than two-ply coated materials, but have a lower flex life. Creasing causes a significant loss in strength for Kevlar laminates. Further research is proposed to reduce the inherent rigidity of the experimental laminate material. Multiaxial textile constructions of Kevlar such as triaxial weaves or parallel, nonwoven yarn arrays laminated to film gas barriers appear to be potential fabrication techniques of considerable merit.

INTRODUCTION

Tethered balloons have been in existence for over a century. They were used in the Civil War as a platform from which field artillery observers could direct fire. During the Second World War, England used them rather extensively as a protection against the aircraft threat. In spite of this long history, the technologies for these vehicles has remained largely undeveloped until recent years. Consequently, these vehicles were quite unreliable and never gained widespread use. In the past decade, however, improvements in materials,

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the increased content and scope of aerodynamics research, and the ability to perform complex structural and stability analyses by automated methods has permitted engineers to review these devices as potentially serviceable and useful systems. The extent of evolution and improvement in these vehicles can be seen by observing Figures 1 through 4.

Figure 1 shows an early version of the barrage balloon. The material was essentially a cotton structural fabric with neoprene outer coating and neoprene between the structural fabric and the bias-ply fabric. Its strength was about 17,500 N/m (100 lb/in.), and its helium permeability was high. This material proved quite durable, however. The cleaning, priming, and bonding operations for making joins were extremely time consuming and costly. The flaccid shape resulted from the fact that the ballonet was inflated by air scoops so the hull was nonrigid in the absence of wind.

Figure 2 whows an improved version of the early barrage balloon that used a more advanced nylon structural material. This material was 0.034 kg/m^2 (1 oz/yd^2) lighter than its predecessor, about 30 percent stronger and had a lower permeability. The rigidity of the vehicle at low wind speeds was improved by the addition of electrically powered blowers.

Figure 3 shows the initial version of the "Family II" shape tethered aerostat. This configuration was rigorously tested in a wind tunnel to investigate the various stability effects of fin size and locations, center of gravity locations, confluence position, etc. The material in this balloon was of conventional coated fabric, but high tenacity Dacron instead of nylon was used for bias and structural ply fabrics, yielding a nearly isotropic material of approximately 26,250 N/m (150 lb/in.) ultimate membrane strength in both the warp and fill directions.

Figure 4 shows a system considered to reflect the current state of the art in aerostat design and manufacturing technique. The major difference between this configuration and the balloon in Figure 3 is a further improvement in material. For a unit weight of only 0.292 kg/m^2 (8.6 oz/yd^2) the ultimate strength of the material was increased to 39.4 x 10^{3}N/m (225 lb/in.) in both the warp and fill directions. This was accomplished with a composite structure incorporating plastic films of Tedlar® and Mylar® laminated to a very strong Dacron fabric. This construction provides a gas barrier with one-fourth the permeability of comparable coated fabrics and adequate shear strength for the intended use.

Figure 5 compares the payload capability for different construction materials of similarly shaped 7,075 m^3 (250,000 ft^3) balloons to be operated at 3,048 meters (10,000 foot) altitude. The coated Dacron, two-ply materials are used in construction of the aerostat in Figure 3. The Dacron-Mylar-Tedlar laminate was used for the system in Figure 4. The latter permits a saving in

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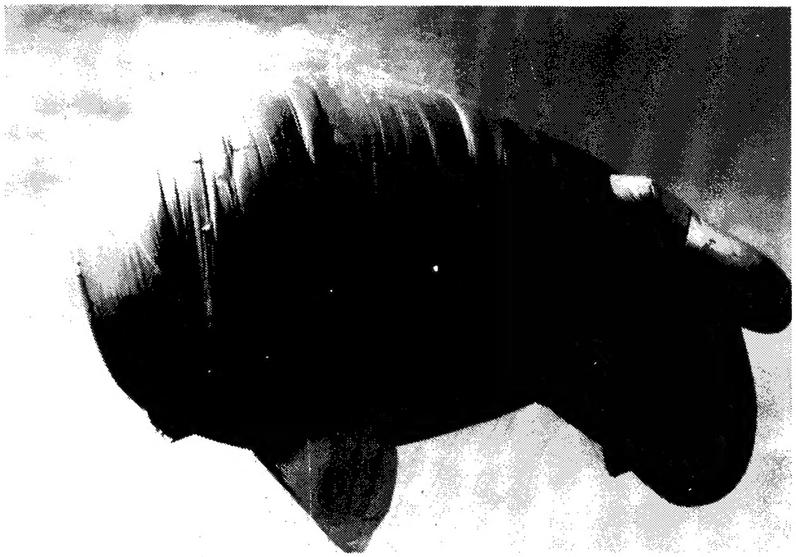


A. EARLY BARRAGE BALLOON

B. MATERIAL PROPERTIES (HULL)

	kg/m^2	(OZ/YD^2)
WEIGHT	.406	(12)
TENSILE		
	N/m	(LBS/IN)
WARP	20,650	(118)
FILL	18,375	(105)
COATING ADHESION	?	
PLY ADHESION	?	
HELIUM PERMEABILITY (l/m^2/24 hrs)	2.5	

C. MATERIAL CONSTRUCTION (HULL)

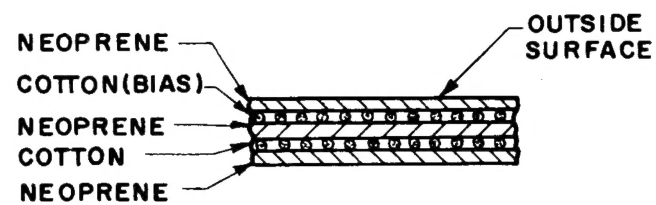


Figure 1. Early Tethered Balloon Design

A. MODIFIED BARRAGE BALLOON

B. MATERIAL PROPERTIES (HULL)

	kg/m^2	(OZ/YD^2)
WEIGHT	.376	(11.06)
TENSILE		
	N/m	(LBS/IN)
WARP	22,400	(128)
FILL	23,975	(137)
COATING ADHESION	1,225	(7)
PLY ADHESION	2,450	(14)
HELIUM PERMEABILITY ($l/m^2/24hrs$)	2.0	

C. MATERIAL CONSTRUCTION (HULL)

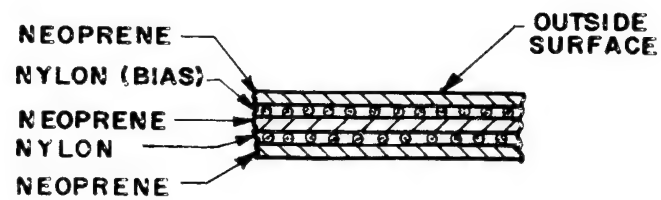
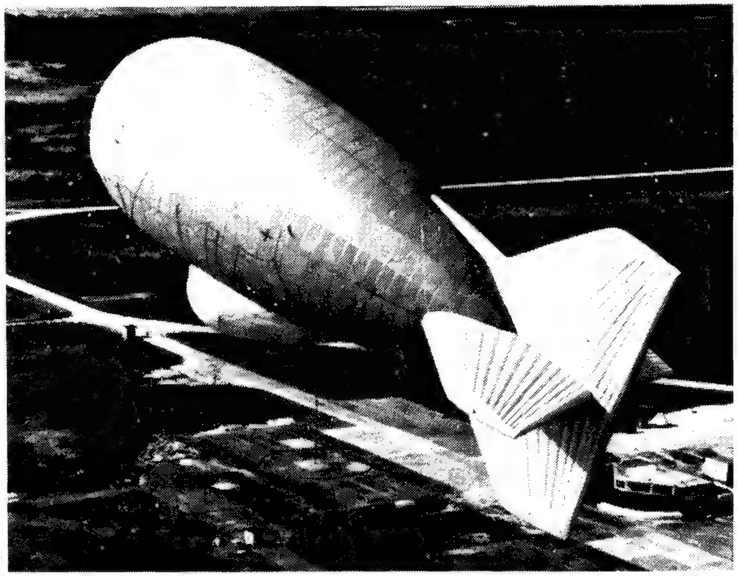


Figure 2. Improved Material on Early Design



A. FAMILY II AEROSTAT, CBV-200A, S/N 201

B. MATERIAL PROPERTIES (HULL)

	kg/m^2	(OZ/YD^2)
WEIGHT	.439	(12.9)
TENSILE		
	N/m	(LBS/IN)
WARP	26,250	(150)
FILL	26,250	(150)
COATING ADHESION	1,225	(7)
PLY ADHESION	787.5	(4.5)
HELIUM PERMEABILITY ($l/m^2/24\,hrs$)	2	

C. MATERIAL CONSTRUCTION (HULL)

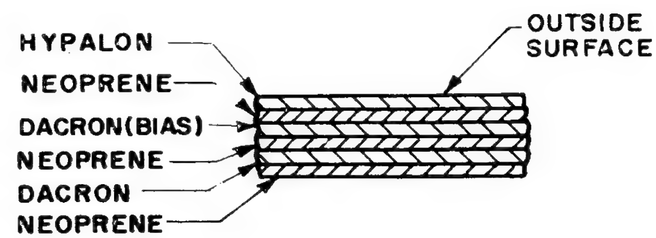
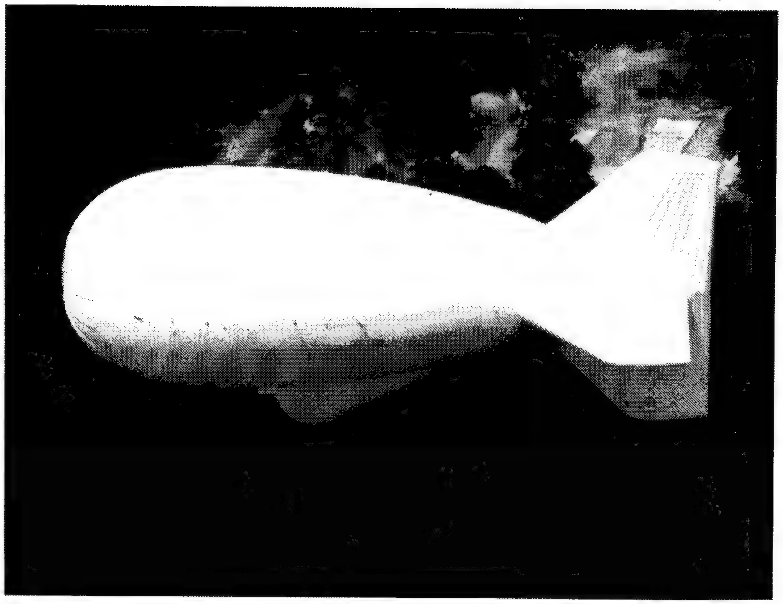


Figure 3. Initial Family II Tethered Aerostat Design



A. FAMILY II AEROSTAT, CBV-250A, S/N 101

B. MATERIAL PROPERTIES (HULL)

WEIGHT	kg/m^2	(OZ/YD^2)
	.292	(8.6)
TENSILE		
	N/m	(LBS/IN)
WARP	39,375	(225)
FILL	39,375	(225)
TONGUE TEAR		
WARP	10,500	(60)
FILL	10,500	(60)
PEEL	1,750	(10)
HELIUM PERMEABILITY ($l/m^2/24$ hrs)	0.5	

C. MATERIAL CONSTRUCTION (HULL)

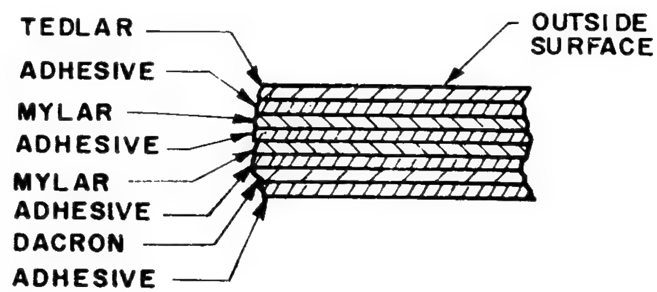
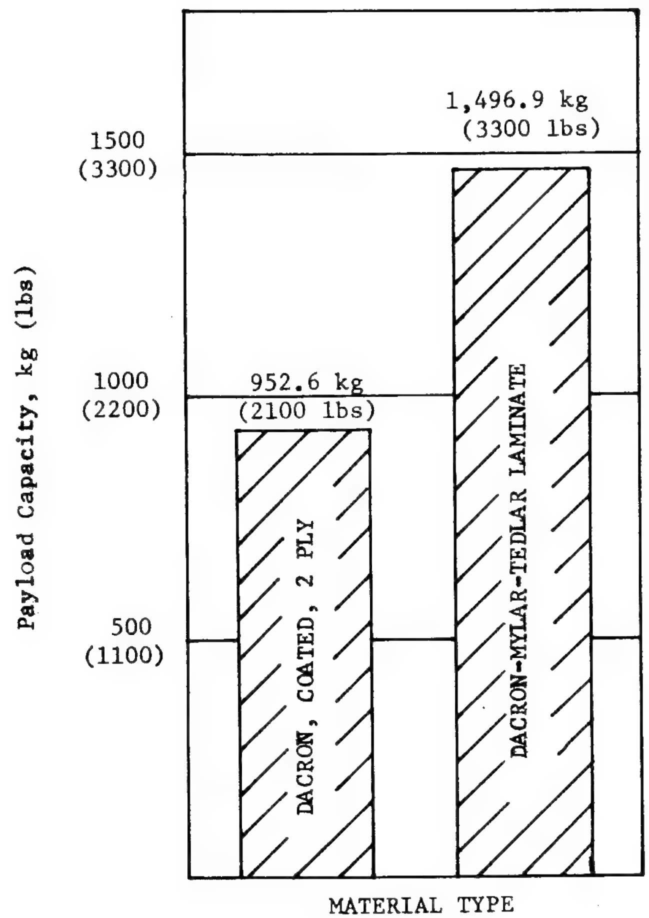


Figure 4. Current State-of-the-Art Tethered Aerostat Design



TYPICAL VEHICLE CHARACTERISTICS

OPERATING ALTITUDE -	3,048 m above MSL (10,000 ft.)
TETHER WEIGHT	297 kg/1000 m (200 lbs/1000 ft.)
SHAPE	Family II(Hull Type III)
SIZE	7,075 m^3 (250,000 ft^3)
DESIGN WINDS	36 m/sec. max. (70 knots max.)

Figure 5. Materials Development Effect on Payload Capacity for Tethered Aerostats

vehicle weight of 554 kg (1,200 lb) which is a 57-percent increase in payload capacity over the former coated material. The dramatic effect of material weight on payload capacity has been the motivation for further research on more advanced materials with greater strength-to-weight ratios, low permeability and high resistance and adaptability to the environment.

Currently, extensive studies are underway in both private industry and the Government on the structural use of filamentary materials, particularly the new organic, high strength, high modulus fiber, Kevlar,* recently marketed by DuPont. These fibers, also designated "PRD-49" (*P*reliminary *R*esearch and *D*evelopment number 49), and "Fiber B", offer strength-to-weight ratios 2 to 3-1/2 times that of Dacron, and ten times that of steel. The strength-to-weight ratio of Kevlar exceeds that of all other materials which can be fabricated using conventional textile technology.

The general object of the studies reported here was to determine whether or not a practical aerostat material could be manufactured using Kevlar. The details, and the effects of high fiber rigidity, strength and weight characteristics under uniaxial and biaxial loading, to obtain quantitative material coefficients, and to determine abrasion resistance, crease effects, peel strength, blocking tendency, helium permeability, and joinery techniques. In investigating the mechanical performance of the various materials reported, a macroscopic approach has been used and no attempt was made to consider the micromechanics of the composites. Macroscopic data are of primary interest for the materials considered, since current technology is essentially limited to the use of average performance characteristics and a scarcity of such data is most evident.

A small quantity of two experimental materials and two conventional materials (as controls) was manufactured by Sheldahl, Inc., Northfield, Minnesota, to contract specifications and tested by the contractor for the pertinent geometric and mechanical characteristics.

In the following sections the design, construction details, test methods, results and conclusions are discussed in detail.

PREPARATION OF EXPERIMENTAL AND BASELINE MATERIALS

One of the experimental materials was designed as a *laminate* construction to yield a strength equal to the traditional material but with a reduction in weight. The second material was designed as a *coated* construction to be equal in weight to its traditional counterpart and to have a higher strength.

The two conventional materials (Figures 3 and 4) were based on a Dacron structural fabric. The two experimental materials employed Kevlar-49 as the

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structural member. Sufficient quantities of these materials were manufactured to produce flat and cylindrical specimens for testing and were manufactured on conventional production equipment at the Sheldahl plant.

Material Design

Material properties which may of concern to the balloon envelope designer are:

Mechanical strength (under tension, tearing, puncture, shear and peel)

Weight

Permeability (to lifting gases)

Environmental strength (resistance to solar-ultraviolet degradation and relative immunity to temperature extremes and effects of moisture)

Efficiency of seams (between panels of the material)

Handling strength (resistance to abrasion and degradation from folding, creasing and other effects of handling, particularly when the balloon is in a flaccid state)

Special requirements (radar reflectivity, nuclear "hardness", etc., peculiar to a balloon application)

Cost (of blank material and of seaming method)

The designers' problem is to formulate a functional composite of fabrics films, adhesives and coatings to obtain an optimum balance of the above properties for a given application.

Figure 6 shows cross sections of the experimental single-ply laminate and the experimental two-ply coated construction. The design concept of construction is indicated on the left of the figure and the actual construction incorporating necessary compromises is shown on the right. The corresponding control materials for these two materials are shown similarly in Figures 3 and 4. In order to achieve structural efficiency in fabricating joints from the experimental materials, the structural lattice provided by the Kevlar fabric was positioned near the inner side of the composite. This geometric feature generally increases the rigidity and stiffness of the finished product and inhibits folding, creasing, packaging and flexing. However, it is considered necessary to achieve adequate load transmission between discontinuous yarns at seams. Joining fabric to fabric reduces the thickness of low-strength lamina that must transmit shear; it minimizes creep in amorphous viscoelastic lamina, and reduces nonplanar deformations. The outer surfaces of the materials are coated with Tedlar or Hypalon to provide a durable, tough abrasive surface along with ultraviolet (UV) protection for the inner constituents. The Mylar adhesive and Kevlar are susceptible to UV degradation and require protection for application where exposure to the solar spectrum for extended periods is a mission requirement. The Tedlar filters out more than 98 percent of the incident UV radiation and is not itself significantly degraded by up to twenty

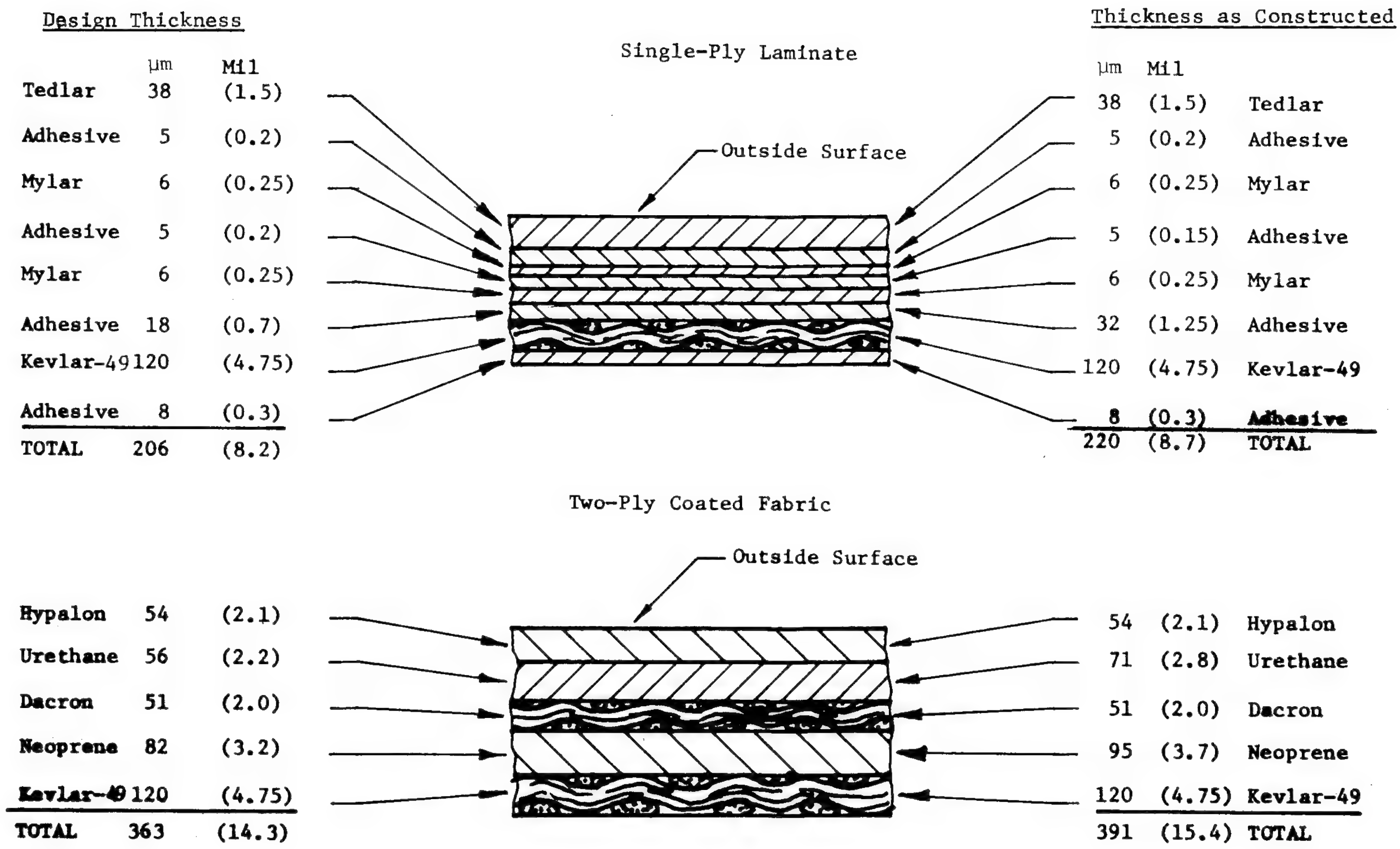


Figure 6. Geometric Configuration of Experimental Materials

years exposure to weathering. To ensure low helium permeability, a bi-lamination of Mylar films is employed in the laminate. The multi-application of adhesive coats to facilitate fabrication and provide a finished inside surface along with the outer abrasion-resistant material afford even greater impermeability. The coated material has slightly higher permeability with the gas barrier being provided primarily by the neoprene and urethane membranes. The urethane also provides some UV protection to the lamina fabric.

Since Kevlar became available only recently, the experimental materials were limited to the available yarn deniers and weave geometry. Lamination and coating processes had to be considered since these are affected by the weave. For example, an open weave with wide spacing between yarns is difficult to laminate because of dimensional instability of the fabric prior to combining with the film. In coating operations, open weave fabrics cause "strike through" or bleeding of the coating through the yarn interstices, which adversely affects coating of the opposite side. A close weave minimizes the weight of coating and laminate adhesive, has good dimensional stability during processing, and is amenable to laminating or coating.

Since the ability for form joints by thermal sealing was a design objective for the experimental materials, the use of coating materials like neoprene was eliminated for exterior surfaces. The experimental fabrics were made as similar in configuration to the traditional Dacron fabrics as possible. For the laminate, the construction is identical to the counterpart control material except for substitution of Kevlar for Dacron and changes in the yarn denier and count in the base fabric. For the coated fabric only the main fabric ply was changed from Dacron to Kevlar. Dacron was used for the bias ply in the coated material because no suitable Kevlar yarn denier and weave patterns were available.

Kevlar yarn size was limited to 195 and 380 denier. Because of the requirement for equal warp and fill strength, a square weave pattern was specified.

Although the tear strength of woven Kevlar had not been measured prior to this investigation, it was assumed to be adequate for balloon use because of high yarn strength. Consequently, a plain weave pattern was used rather than a more complicated basket weave. If it later became necessary to enhance the tear strength, basket-weave Kevlar could be substituted.

It was found that the experimental laminate material could be made equal in strength to the standard laminate if the Kevlar fabric weighed approximately 0.061 kg/m^2 (1.8 oz/yd^2) which would give about 47,259 N/m (270 lb/in.) uniaxial strength in both warp and fill directions. For the second coated material, the primary ply Kevlar fabric was made equal in weight to that of its traditional Dacron counterpart—0.095 kg/m^2 (2.8 oz/yd^2). This was found to have a strength of about 73,500 N/m (420 lb/in.) in both warp and fill directions.

Properties of the constituent Kevlar fabrics used in the laminate and coated materials are presented in TABLE 1-A. The actual weights of the fabrics used in the prototype materials were very close to the theoretical weights. The tested strength of the 0.095 kg/m^2 (2.8 oz/yd^2) fabric was almost exactly as predicted. However, the strength of the 0.061 kg/m^2 (1.8 oz/yd^2) fabric was slightly lower than the theoretical value. The 0.095 kg/m^2 (1.8 oz/yd^2) fabric was a conventional weave, whereas the 0.061 kg/m^2 (1.8 oz/yd^2) fabric is a loose weave. The yarn was washed of lubricants to improve the adhesion. A low twist value of four turns/m (0.1 turn/in.) in the yarn is typical. Low twist yarn yields thin lamina of low abrasive finish. No ripstop features were included in the weave, however, such modifications as a basket weave instead of a plain weave could easily be added. Tha basic mechanical properties of the Dacron fabrics used in this fabrication are given in TABLE 1-B. The pertinent properties of interest for the constituent membranes used are provided in TABLE 1-C. These data are for the Tedlar, polyester adhesive, Mylar, Hypalon, neoprene, and urethane. The adhesive is a significant proportion of the single-ply laminate and its properties and performance are important features in the mechanical behavior of the composite structure, primarily at low temperature. A typical environment for materials applications reported here is -34.4°C to 45.6°C (-30°F to 112°F). The membranes and fibers remain ductile at these temperatures, but the adhesives used become glasseous and brittle. This can produce inter-laminar deterioration and premature structural failure from loading at cold temperatures. Parallel research is being conducted at Princeton University to obtain suitable adhesives that will not undergo glasseous transitions for temperatures above -67°C (-90°F). The status of this research was not sufficiently advanced to permit the use of these experimental adhesives in the materials discussed here.

Lamination Procedure

The experimental laminate and its control material were manufactured in pilot-scale quantities on Sheldahl production laminators, see Figure 7.

Equipment. — The laminator shown in Figure 7 consists of three parts: an adhesive coating section, a drying section, and a combining section. When laminating two materials, one is coated with adhesive and the other becomes the combining material. The material to be coated travels from an unwind station and over a drum rotating in an adhesive bath. The coated ply then travels through a drying tunnel to remove adhesive solvents. It then is joined to the combining material and passes between a pair of rolls which apply sufficient pressure and heat to fuse the adhesive layer between the plys. The product is rewound for storage as the adhesive cools. When combining films, the product is simply wound upon itself at the take-up station. Lamination of fabric to films may require the insertion of a release sheet at the take-up point to prevent adhesive exposed by the fabric interstices from sticking or transferring to the opposite side of the product. Polyethylene film 12 to 25μ (0.5 to 1.0 mil) thick or silicone treated, 18 kg (40 pound) kraft paper are commonly used for this purpose.

TABLE 1-A

PROPERTIES OF KEVLAR-49 FABRIC COMPONENTS

Metric Units (English Units in Parentheses)

Characteristic \ Application	1-Ply Laminate Experimental (Figure 6)	2-Ply Coated Experimental (Figure 6)
Weight	0.060 kg/m^2 (1.8 oz/yd^2)	0.090 kg/m^2 (2.7 oz/yd^2)
Strength: Warp	39,400 N/m (225 lb/in)	74,400 N/m (425 lb/in)
Fill	39,400 N/m (225 lb/in)	74,400 N/m (425 lb/in)
Weave Type	Plain	Plain
Fabric Finish	Scoured	Scoured
Yarn Count	13/cm x 13/cm (34/in x 34/in)	20/cm x 20/cm (50/in x 50/in)
Yarn Size	195 Denier	195 Denier
Yarn Twist	4 turns/m (0.1 turn/in)	4 turns/m (0.1 turn/in)
Filament Count	134/yarn	134/yarn
Filament Strength	3620 MN/m^2 (5.25×10^5 lb/in^2)	3620 MN/m^2 (5.25×10^5 lb/in^2)
Filament Modulus	131 GN/m^2 (1.9×10^7 lb/in^2)	131 GN/m^2 (1.9×10^7 lb/in^2)
Density	1450 kg/m^3 (.052 lb/in^3)	1450 kg/m^3 (.052 lb/in^3)

TABLE 1-B

PROPERTIES OF DACRON FABRIC COMPONENTS

Metric Units (English Units in Parentheses)

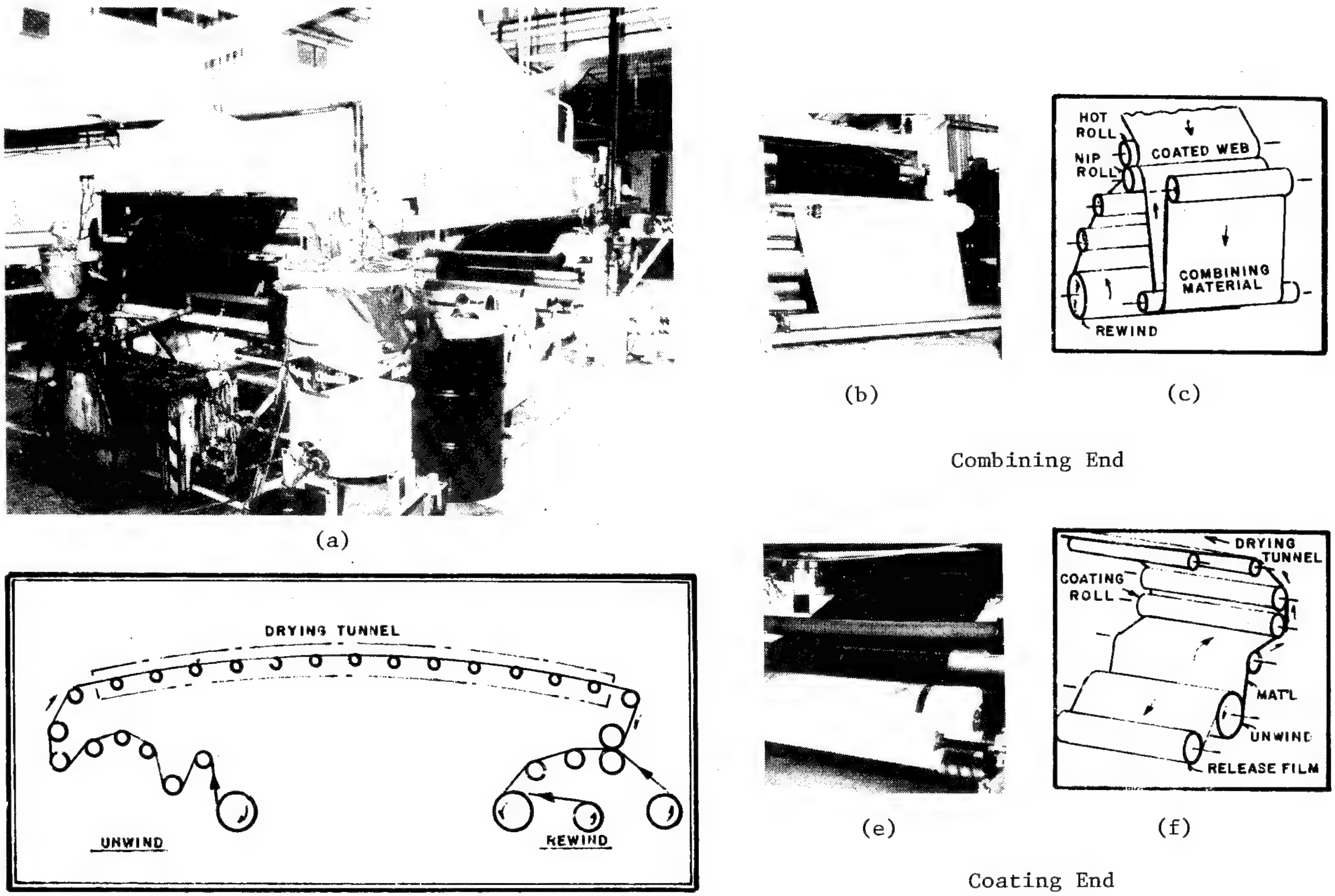
Characteristic \ Application	2-Ply Coated Experimental (Figure 6)	2-Ply Coated Control (Figure 3)	1-Ply Laminate Control (Figure 4)
Weight	0.047 N/m^2 (1.4 oz/yd^2)	0.108 N/m^2 (3.25 oz/yd^2)	0.126 N/m^2 (3.8 oz/yd^2)
Strength: Warp	6,100 N/m (35 lb/in)	27,000 N/m (155 lb/in)	39,400 N/m (225 lb/in)
Fill	6,100 N/m (35 lb/in)	27,000 N/m (155 lb/in)	39,400 N/m (225 lb/in)
Weave Type	Plain	Plain	Plain
Fabric Finish	Scoured and Heat Set	Scoured and Heat Set	Scoured and Weave Set With 5-10% by Weight of Polyvinyl Acetate
Yarn Count	39/cm x 39/cm (98/in x 98/in)	20/cm x 20/cm (50/in x 50/in)	5/cm x 5/cm (13/in x 13/in)
Yarn Size	40 Denier	220 Denier	1,000 Denier
Yarn Twist	9 turns/cm (23 turns/in)	1 turn/cm (3 turns/in)	4 turns/m (0.1 turns/in)
Filament Count	27/yarn	50/yarn	192/yarn
Filament Strength	570 MN/m^2 (0.83×10^5 lb/in^2)	1030 MN/m^2 (1.5×10^5 lb/in^2)	1030 MN/m^2 (1.5×10^5 lb/in^2)
Filament Modulus	13.8 GN/m^2 (2×10^6 lb/in^2)	13.8 GN/m^2 (2×10^6 lb/in^2)	13.8 GN/m^2 (2×10^6 lb/in^2)
Density	1380 kg/m^3 (.05 lb/in^3)	1380 kg/m^3 (.05 lb/in^3)	1380 kg/m^3 (.05 lb/in^3)

TABLE 1-C

PROPERTIES OF FILM, ADHESIVE, AND COATING COMPONENTS

Metric Units (English Units in Parentheses)

Characteristic / Component	Application	Description	Tensile Strength @ 22°C (72°F)	Density
Tedlar	1-Ply Laminate Control - Fig. 4 and Experimental - Fig. 6	DuPont polyvinyl fluoride film, type 30, adhereable both sides, "L" gloss, titanium dioxide pigment	55 MN/m^2 (8000 lbs/in^2)	1770 kg/m^3 (.064 lbs/in^3)
Mylar	1-Ply Laminate Control - Fig. 4 and Experimental - Fig. 6	DuPont type S, polyester film, 0.25 mil thick	138 MN/m^2 (20,000 lb/in^2)	1390 kg/m^3 (.05 lbs/in^3)
Adhesive	1-Ply Laminate Control - Fig. 4 and Experimental - Fig. 6	Aliphatic polyester resin cured with di-isocyanate for hydrolytic stability	10 MN/m^2 (1500 lbs/in^2)	1240 kg/m^3 (.045 lbs/in^3)
Hypalon	2-Ply Coated Control - Fig. 3	Chlorosulfonated polyethylene with aluminum pigment	14 MN/m^2 (2000 lbs/in^2)	1390 kg/m^3 (.05 lbs/in^3)
	and Experimental - Fig. 6	Chlorosulfonated polyethylene with titanium dioxide pigment	14 MN/m^2 (2000 lbs/in^2)	1250 kg/m^3 (.045 lbs/in^3)
Neoprene	2-Ply Coated Control - Fig. 3 and Experimental - Fig. 6	Low, temperature, non-crystalline polychloroprene with lead cure system for hydrolytic stability	24 MN/m^2 (3500 lbs/in^2)	1250 kg/m^3 (.045 lbs/in^3)
Urethane	2-Ply Coated Experimental - Fig. 6	B. F. Goodrich Estane 5740-X210 low temperature polyurethane formulated for high hydrolytic stability, ultraviolet resistance and heat sealability. Carbon black pigment. Fabric surfaces to be coated are treated with isocyanate type primer.	34 MN/m^2 (5000 lbs/in^2)	1200 kg/m^3 (.043 lbs/in^3)



(a) (b) (c) Combining End

(d) (e) (f) Coating End

Figure 7. 64-Inch Laminator

Lamination sequence. — In the case of the laminates, the aliphatic, polyester adhesive is applied as an 8-percent solids solution in methylene chloride. Because the resin and cure agent are dispersed, the solution has a pot life of approximately eight hours. Water may react with the cure agent before the agent acts on the resin, producing a structurally inferior product. The following must be religiously observed to minimize water contamination:

- Cure agent is stored in airtight containers and dispensed by introducing dry nitrogen gas into the containers.
- Solvent grades with a low water content are procured and stored in tanks designed to prevent accumulation of water condensate.
- Exposure of adhesive solution to air with a high relative humidity is avoided as far as possible.
- Reverse coating rolls and other conductive metal parts of the adhesive handling system which cool by solvent evaporation must be heated above the dew point of the air in the coating room.

Single-ply laminates were assembled by applying the adhesive solution to one layer of Mylar with a reverse roll coater, extracting the solvent in a drying tunnel and immediately laminating the coated sheet to the Tedlar film. The other Mylar layer was then coated and bonded to the previous laminate. Finally, the three-film laminate was coated and laminated to the fabric. A final pass applied a primer coat of adhesive to the fabric side.

Handling. — Requirements for handling the various layers are equally important to the process result. Since all the plastic films had been used previously in the conventional laminate material, the only new constituent was the Kevlar fabric. The low elongation of Kevlar results in a fabric easily guided by the laminator web handling equipment. A minimum differential deformation was required between the film and the fabric. Deformation, flatness and alignment were well within normal specifications. The final laminate was extremely stable and easy to handle. Since a satisfactory product was so easily achieved, it is believed that no particular problems would arise in the event large-scale production were required for this laminate.

Coating Procedure

The coating process was performed by the Haartz Mason Company as a subcontractor to Sheldahl. Sheldahl representatives were in attendance at the subcontractor's plant during the coating and combining of the constituents.

Coating process. — Coating equipment consists of mixing machines for the various coating compounds and machines for applying these compounds to fabrics. Commonly, a knife-over-roll process is used which restricts the amount of coating which can be applied on each pass. The fabric first passes the knife-over-roll coater, then travels through a drying tunnel to remove solvents.

The dried coated material is rewound and the process repeated as many times as required to achieve the desired coating thickness.

For the experimental fabric described, 0.048 kg/m^2 (1.4 oz/yd^2) Dacron was coated with neoprene and cut into rhombus shapes at 45° to the warp direction. These segments are rotated to place warp and fill at 45° to the machine direction (biasing) and joined at their edges. The Kevlar was then coated with neoprene and combined with the Dacron bias ply by a process called doubling—Neoprene side to Neoprene side. The Dacron side was coated first with urethane and then with hypalon. The product was trimmed to the desired width and wound for storage and transit.

Handling. — Dimensional stability of the Dacron bias ply was very poor because of its lightweight. Strike through of the coating material to the opposite side of the fabric was difficult to control. Because of the difference in modulus of the Dacron bias and Kevlar primary piles and because of the coarseness of the automated web guiding equipment, it was virtually impossible to eliminate wrinkling of the plies.

Several process changes would be required before large-scale production of coated materials with a Kevlar primary ply would be practical. To improve the operation, the vendor proposed decreasing the yarn count in the Kevlar fabric and using 0.061 kg/m^2 (1.8 oz/yd^2) Dacron fabric for the bias ply to add stability to the bias and reduce stability in the Kevlar to make the two materials more compatible. Another alternative would be to use Kevlar for both bias and primary plies. Kevlar yarn in deniers smaller than currently available would be required to make this practical.

TEST PROGRAM

A comprehensive test program was performed on the two experimental materials and the two conventional controls to determine their strength and durability. Tests of uniaxial and biaxial strength, inter-laminar peel strength, crease degradation, blocking, tear strength, abrasion, flexibility and permeability were also performed. The test procedures and test equipment are discussed in the following paragraphs.

Strength Tests

Ultimate tensile strength and elastic properties were determined by uniaxial and biaxial testing. Inter-laminar bond strength was investigated by peel tests.

Uniaxial tensile tests. — The uniaxial or two-dimensional tensile tests conducted on these fabrics are performed using Federal Test Method 5102, which employs a sample size 0.025 meter (1-inch) wide and a 0.076-meter (3-inch) grip separation. The grip separation rate for these tests is 0.305 meter

(12-inch) per minute. Five specimens for each test condition were used as a sample population. Test temperatures were 60°C, 22°C, and -51°C (140°F, 74°F, and -60°F).

All tests were conducted using a Model 114 Instron Testing Machine, shown in Figure 8. In Figure 8(a) the Instron tester is shown without the environmental chamber which is the configuration for making room-temperature tests. Figure 8(b) shows the Instron with the environmental chamber attached for testing at elevated and sub-zero temperatures.

For the laminates, tests were conducted on the finished materials as well as on the various film plies which comprise the gas barrier and outer surface. Figures 9 and 10 show sample preparation methods, sample mounting techniques, and typical charts. The Thwing-Albert sample cutter shown in Figure 9 provides a uniform, precision sample width of 25.4 mm. One cutter was used for thin film specimens and a separate cutter used for the heavier fabric based specimens to preserve the quality of cut edges on the thin film specimens.

Typical samples of untested and failed specimens of finished materials are shown in Figure 10 along with a specimen mounted in the Instron jaws ready for testing. A chart recording displayed in Figure 10(c) shows the typical stress-strain relationship to failure for each of the four materials tested. The difference in grip travel between the two Kevlar-based materials and the Dacron-based materials indicates the low elongation to failure of Kevlar.

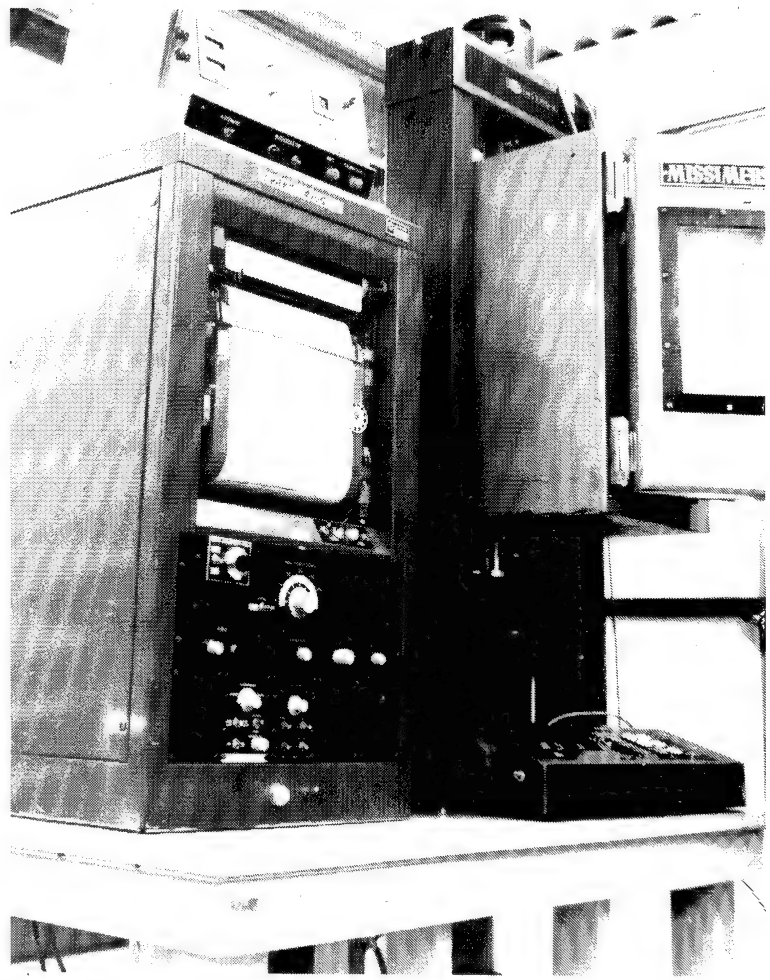
Generally uniaxial coupon tests are not a reliable indication of material strength. This is particularly true for composites with diagonal or bias structural elements. In addition, for woven fabrics the stability of the weave, crimp, and yarn interlock effects are degraded in the one dimensional stress field. However, the unixial test is a simple, fast, and inexpensive method adequate as an indication of strength and anisotropy and as a quality control procedure. The deficiency of uniaxial coupon tests to fully involve and stress the structural features of laminated fabric materials has been the motivation for more sophisticated multi-axial tensile testing on cylindrical material specimens.

Biaxial tensile testing. — Complete characterization of even a single material's strength under combined direct and shear loading would be a formidable task. In this investigation, testing was restricted to a comparison of the experimental and control materials at combined loading conditions representative of the principle stresses in large spherical and cylindrical balloon structures:

Condition	A	B	C
Direct Stress Ratio (warp/fill)	1:1	2:1	2:1
Direct Stress Magnitude (warp)	(To ultimate)	(To ultimate)	Ultimate/3
Shear Stress Magnitude	zero	zero	(To ultimate)

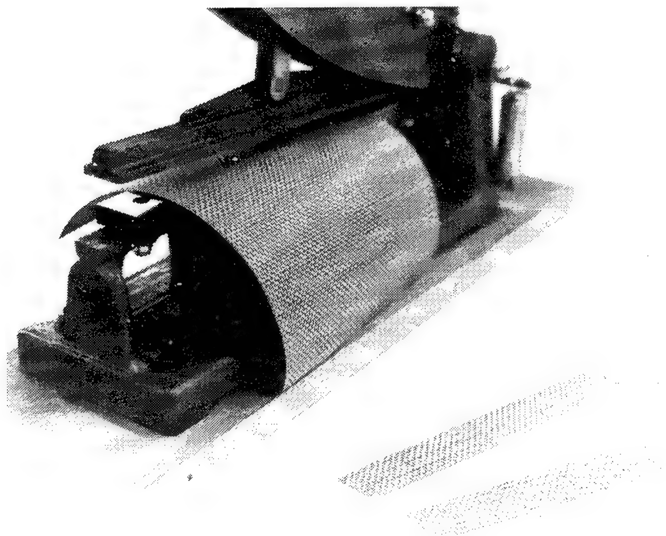
Approximately 30 specimens of each material were prepared to give 3 replicates of each condition A, B, and C and at each of the temperatures -51°, 22° and 60°C.

(a) Ambient Temperature Test Arrangement

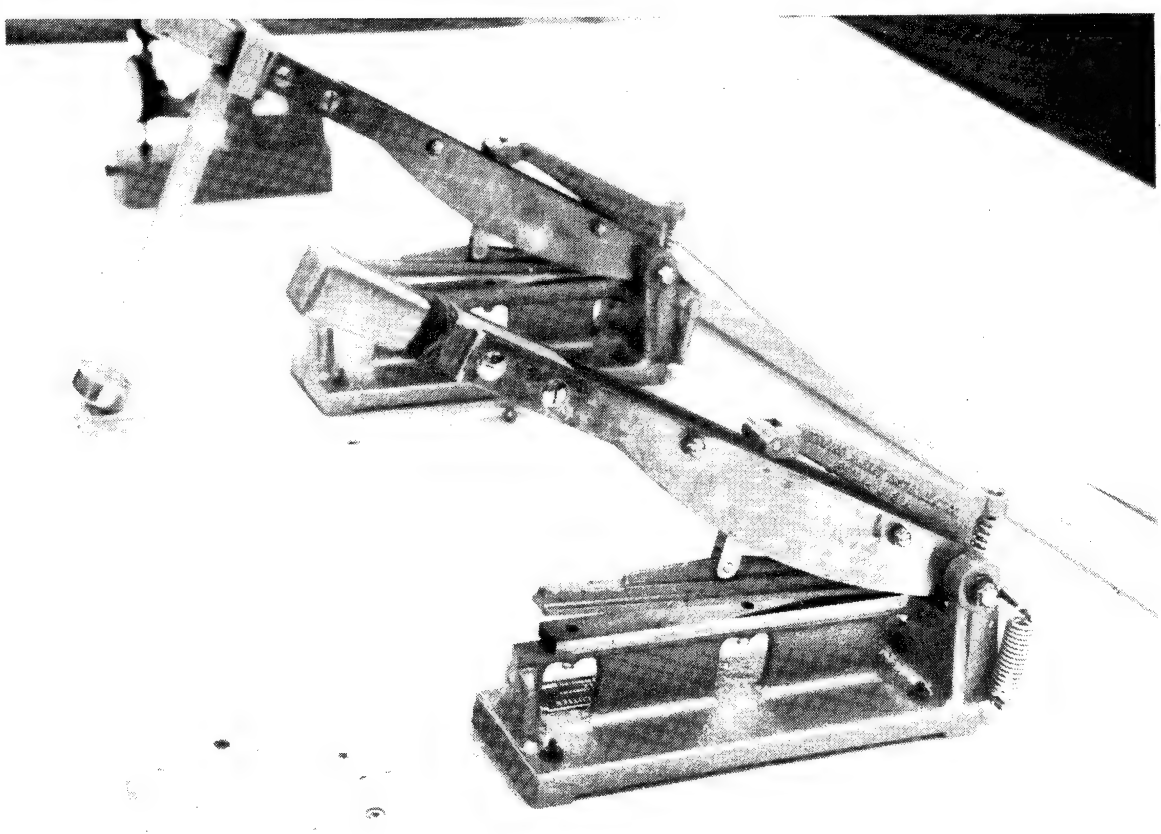


(b) Variable Temperature Test Arrangement

Figure 8. Instron Tensile Test Facility

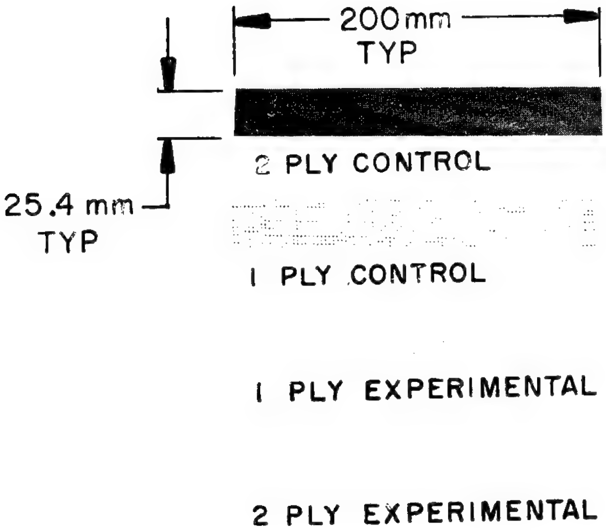


(a)

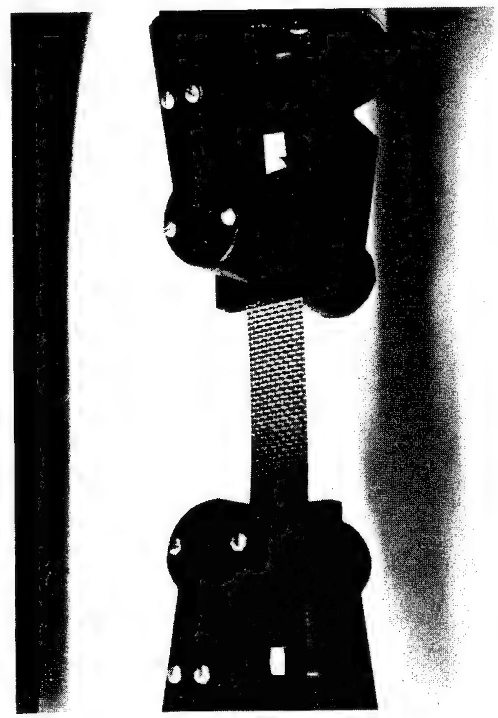


(b)

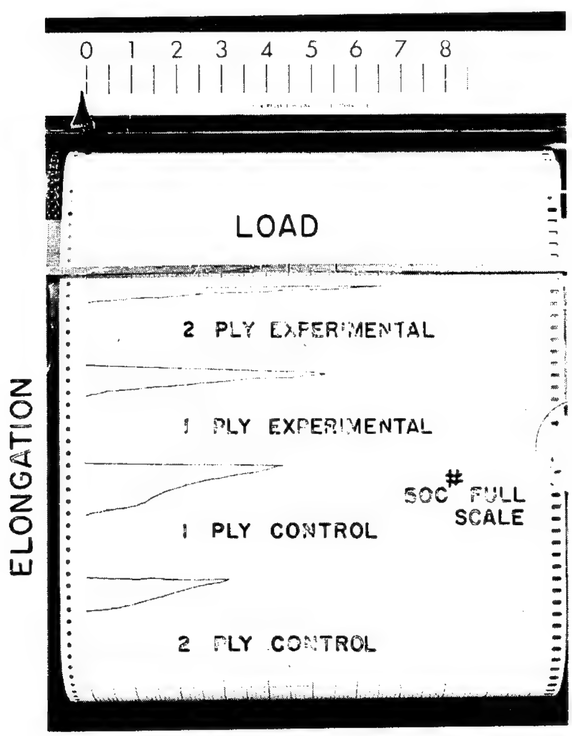
Figure 9. Thwing-Albert Test Specimen Cutters



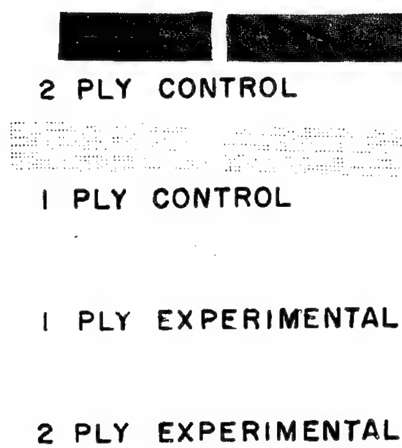
(a) Prepared Test Specimens



(b) Test Mounted Specimen



(c) Typical Stress-Strain Recordings



(d) Failed Specimens

Figure 10. Uniaxial Tensile Tests

Biaxial testing was performed on a fixture capable of applying variable hoop, axial and shear loads to material formed into a cylindrical sleeve (Figure 11). The sleeve ends were clamped to circular end plates forming a sealed chamber and hoop loads were controlled by varying either fluid or gas pressure inside. Axial and torque loads were controlled by varying pressures applied to fluid-driving elements acting on the movable end plate.

The equipment described was originally developed for testing light-duty balloon materials (Reference 1). The apparatus was modified before performing the first series of tests described in this report. Further modifications were made to correct a number of deficiencies and a second series of tests conducted on the same materials.

Originally, internal pressurization produced the axial loads which were slightly less in capacity than half the hoop direction loads because of the rod area losses. To obtain independent control of axial force, a pneumatic cylinder was added in the first series of tests to drive the circular end plates apart along their common axis. Since the 8,900 N (2000 lb) force available was marginal with respect to the strength of the materials tested, a hydraulic cylinder was substituted for the second test series to provide driving forces up to 89,000 N (20,000 lb).

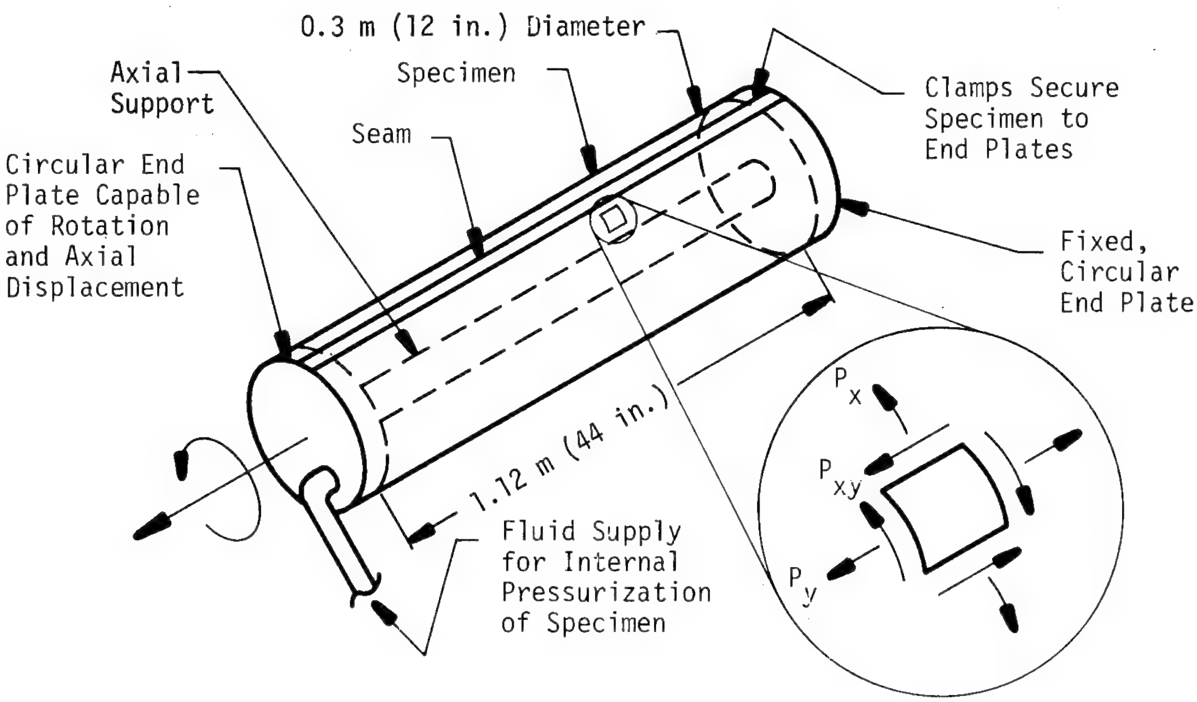


Figure 11. Biaxial Tensile Test Method (P_x, P_y, and P_{xy} are the warp direction, fill direction, and shear membrane forces in specimens, respectively.)

In the first test series, shear loads were applied by turning the movable end plate by means of a pneumatic cylinder and cable wrapped around the edge of the clamping ring (left side of Figure 12). The range (20° rotation) and available torque, 620 m-N (5500 in.-lb) of this arrangement proved to be marginal for the materials of this investigation. For the second test series, shear loads were applied by a hydraulic rotary actuator with about three times the range and torque capability, and mounted between the end plates on the specimen axis.

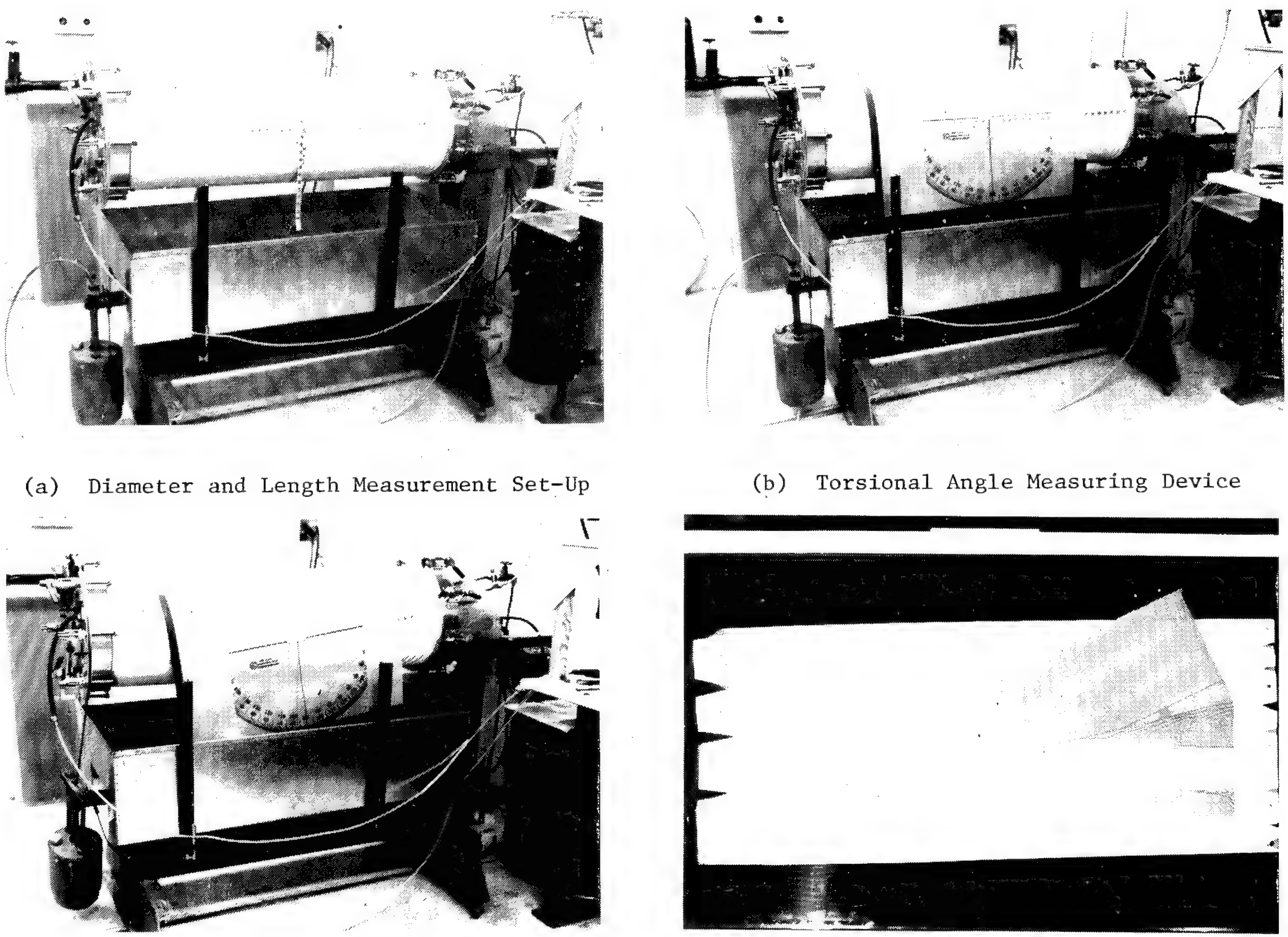
Initially, axial and shear specimen strains were measured manually by a tape and protractor as shown in Figure 12 (a), (b), and (c). Improvements followed to increase accuracy and efficiency, and to allow remote readout by means of the potentiometers and mechanisms shown in Figure 13 (a) and (b).

The heavy materials tested were considered both a noise and safety problem when loaded to the burst level. To obviate the considerable acoustic and ballistic hazards to personnel, hydraulic loading was tried by pressurizing the specimen with a mixture of alcohol and water. The principal difficulties with this method were:

a. Distortion of the material specimen from a true, axisymmetrical form because of the fluid weight;
b. Delamination of the materials caused by fluid leaking into imperfections in the material surface;
c. The extensive test cycle time produced by the small size of equipment used to heat, cool, and pump the fluid, particularly at -51°C (-60°F) where the liquid became a slurry;
d. Control of the fluid after rupture.

The second series of tests was conducted using air pressure to produce the hoop loads and the apparatus and controls were placed in separate rooms to protect the operator.

For tests at extreme temperatures, an insulated, coaxial enclosure was fitted over the specimens. The insulation sustained considerable damage during specimen burst and frequent repairs were necessary. Non-ambient temperatures in the first test series were obtained by heating or cooling the water-alcohol mix used to fill and pressurize the specimens. In the second series, air was passed over finned, electric strip heaters and circulated between specimen and enclosure (Figure 14) to obtain elevated temperatures. Low temperatures were obtained by similar circulation of vapor evaporated from liquid nitrogen. A thermocouple on the specimen and a set point temperature control were used to adjust current in the heater or the nitrogen supply. Figure 14 indicates temperatures measured at five or six points on a specimen inside the chamber. These were observed to vary by ± 17°C from a mean value of +55°C and by a similar amount near a mean of -65°C. A much faster circulation rate and extensive chamber modifications would be required to significantly reduce the temperature distribution. This was not pursued because temperature variations in the first test series were observed to have little effect on biaxial strength.



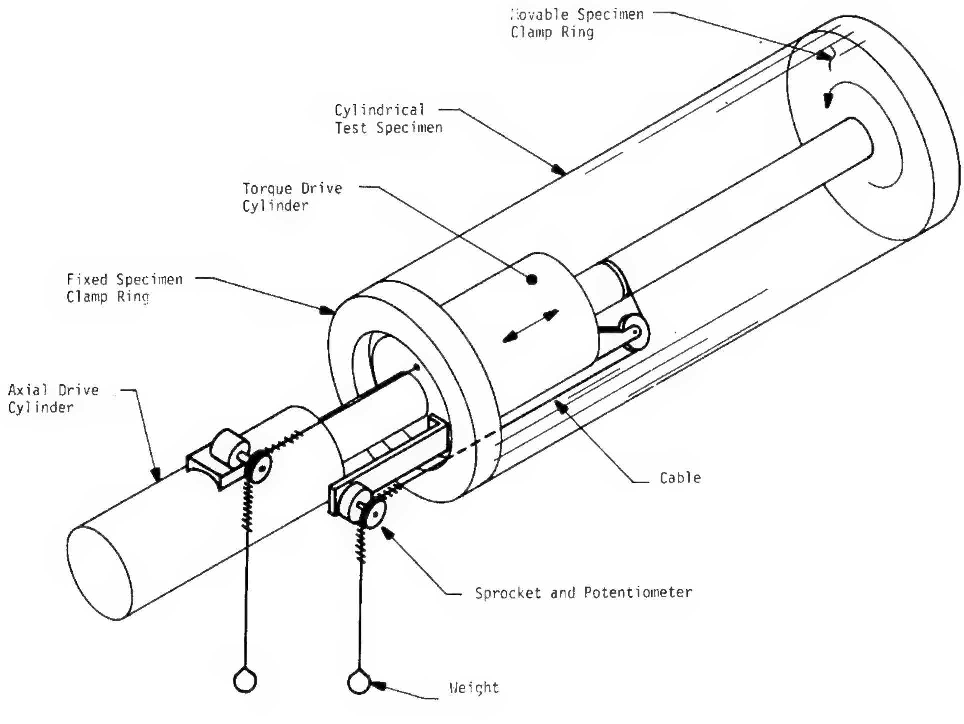
(a) Diameter and Length Measurement Set-Up

(b) Torsional Angle Measuring Device

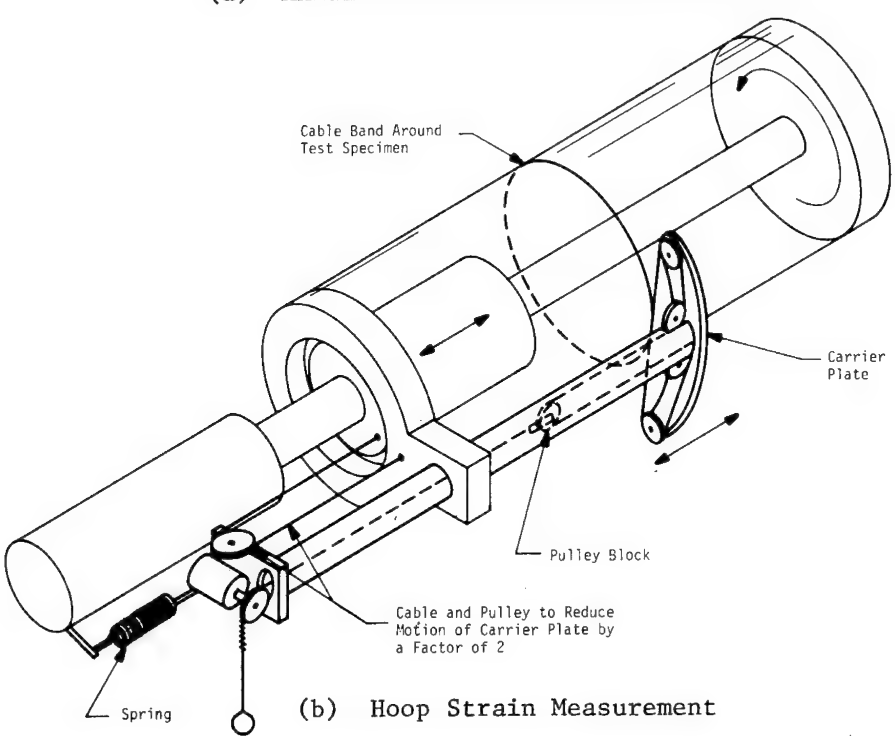
(c) Test with Torsional Load Applied

(d) Failed Specimen

Figure 12. Cylinder Test Apparatus - Series 1 Tests

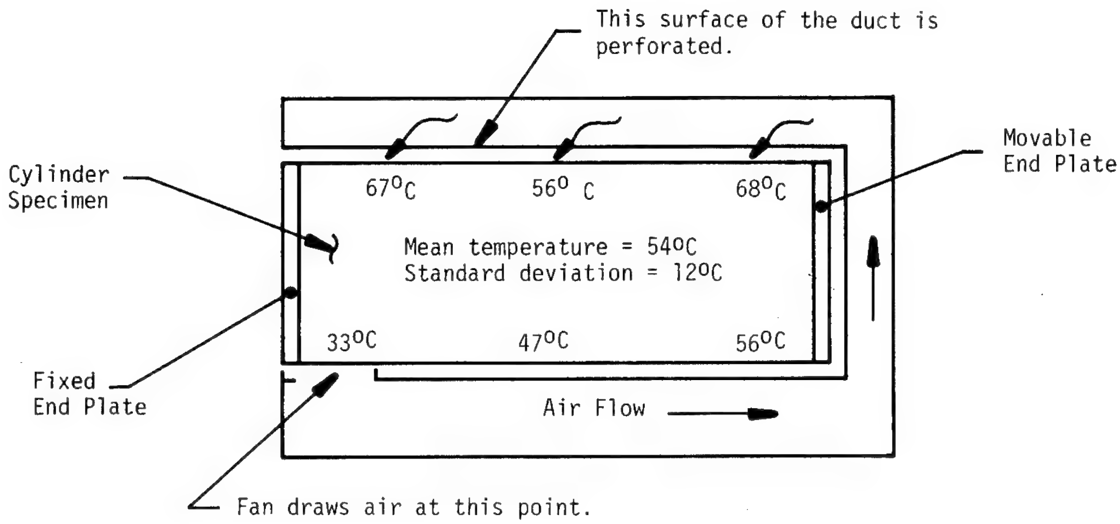


(a) Axial and Shear Strain Measurement

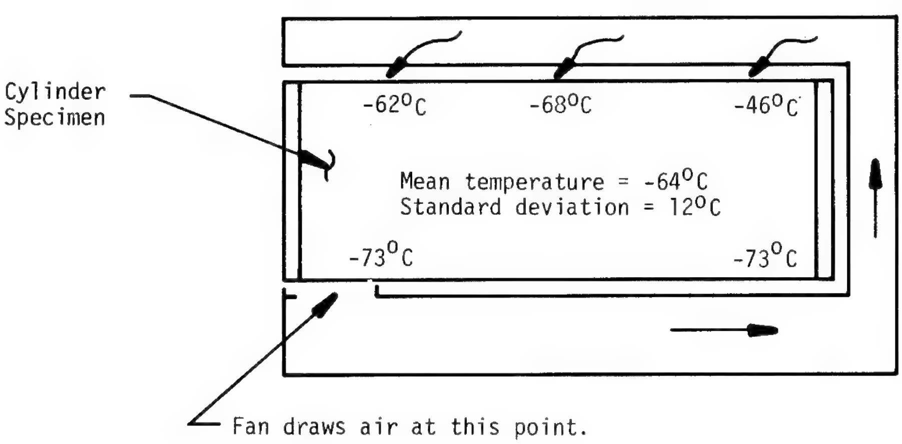


(b) Hoop Strain Measurement

Figure 13. Axial, Shear and Hoop Strain Measurements —Series 2 Tests



(a) Elevated Temperature



(b) Low Temperature

Figure 14. Representative Temperature Distributions in Environmental Chamber.

All sleeve test specimens were provided with one structural seam to close the edges of the cut-out piece, as shown in Figure 15 and one dummy seam, made with the same tape materials, diametrically opposite and aligned parallel to the sleeve axis. For fabric test materials, it is difficult or impossible to make sleeve specimens without seams. Techniques for winding yarns around a tube of plastic film to produce seam-free sleeves of reinforced membranes have been investigated at the Langley Research Center.

For light-duty materials the sleeve-shaped test specimens had been secured to the end plates by screw-actuated band clamps, cushioned with rubber gaskets (Reference 1). This arrangement was inadequate for the heavier materials of this investigation. The first test series was conducted with a wedge ring and mating insert bolted together to clamp the sleeve end. Figure 16 outlines this mounting sequence. A pressurized torus between the specimen and the end plate was used to provide a gas seal for internal pressurization of the sleeve.

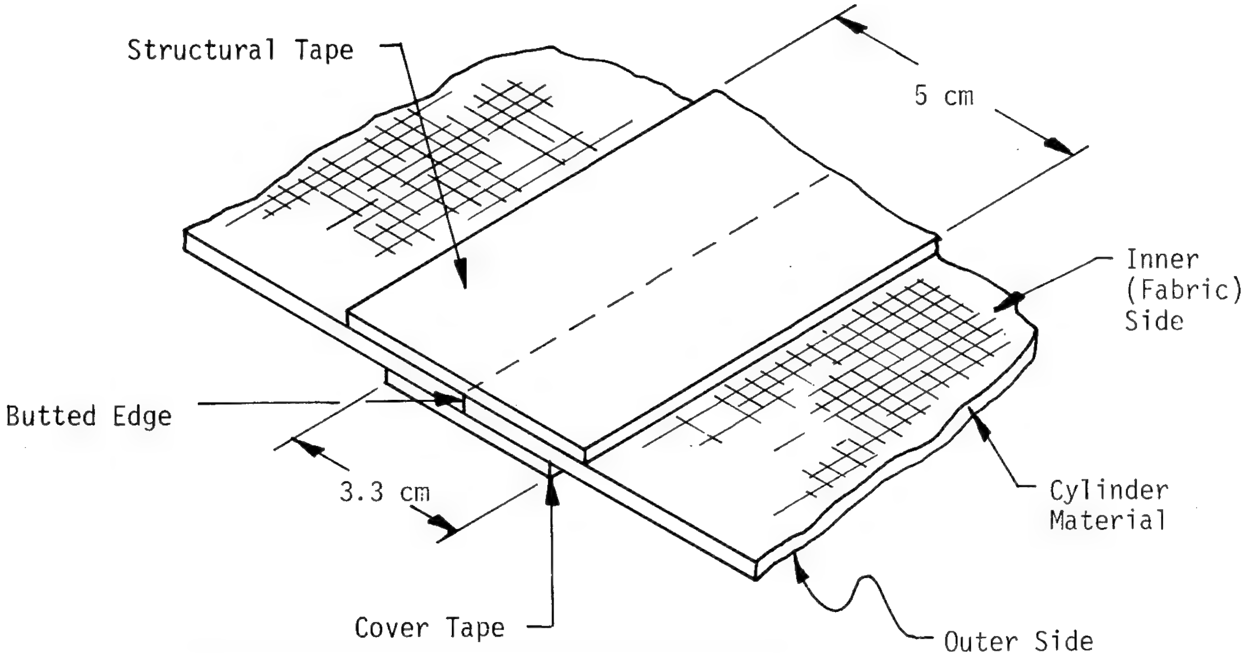
Figure 17 illustrates the elements of the modified clamp, and Figure 18 shows the mounting sequence. Figure 18(a) is the base (movable) end plate with the 1.5-mm thick neoprene rubber sealing gasket in place. Figure 18(b) shows the sleeve specimen in place with an additional gasket band over the pressure face and tabs at the specimen end folded over the steel snubbing ring. The outer clamping ring is dogged in place in Figure 18(c). Figure 18(d) shows the specimen ready for testing after seating the material in the clamp by cycling the axial specimen load between zero and about 2600 N/m (15 lb/in.)

Peel strength testing. — Peel strength measurements on film-to-fabric bonds were made in accordance with American Society for Testing and Materials D1876, Figure 19(a). Film-to-film bonds were tested using Q000066, Method A, Appendix A, illustrated in Figure 19(b). In the former method, both adherends are allowed to flex near the line of failure through angles of approximately 90 degrees. The equilibrium angles of flex vary depending on the relative stiffness of the adherends. In any case, no external control over the angle was exercised. Under Q000077, Method A, one adherend is flexed through 90 degress or less and the other through a very small angle, Figure 19(b). Because of asymmetry in adherend flexing, all film-to-film peels were made from the outer surface of the laminate by mounting the fabric side against the drum.

Film-fabric peels under D1876 were run at 0.305 meter (12 inches) per minute and the film-to-film peels at 0.051 meter (2 inches) per minute. Peel strength is rate sensitive, and measurements made at different rates cannot generally be compared.

Five samples from the beginning and end of production runs were tested at 22°C (72°F). One end of each specimen was immersed in methylene chloride for 10 to 20 seconds and the plies separated in preparation for testing, Figure 19(b). Values obtained over the initial 12 mm (0.5 in.) of peel were disregarded because of the wicking of solvent along the yarns.

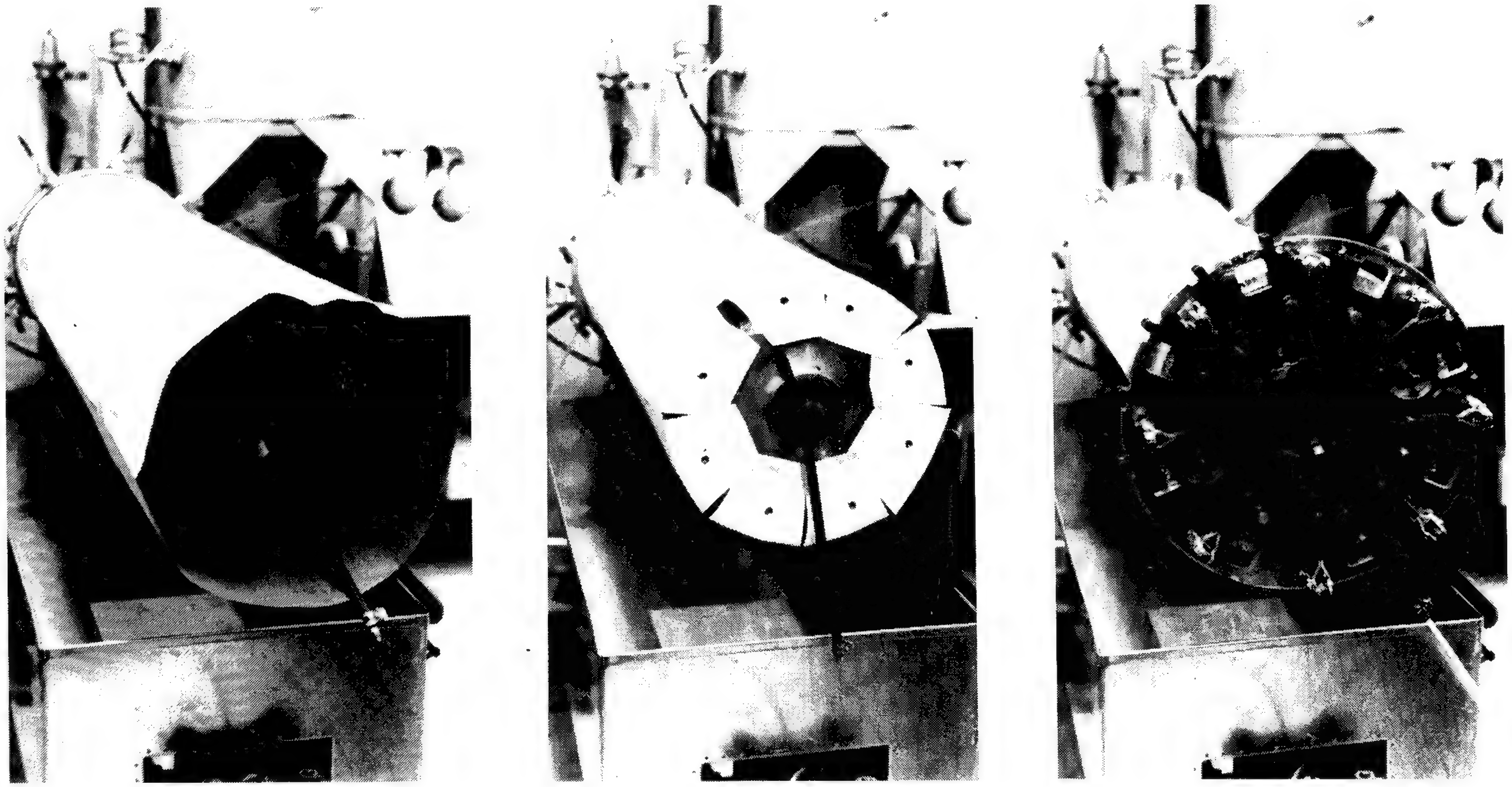
The specimen in Figure 20(a) is representative of the appearance of film fabric peel specimens after testing. Some yarns transverse to the specimen axis would pull out of the separating fabric ply and remain bonded to the film side.



Cylinder Material	Control		Experimental	
	1-Ply	2-Ply	1-Ply	2-Ply
Structural Tape	T126600	T126600	Coated Kevlar Laminate	Coated Kevlar Laminate
Cover Tape	T126700	D048700	T126700	D048700

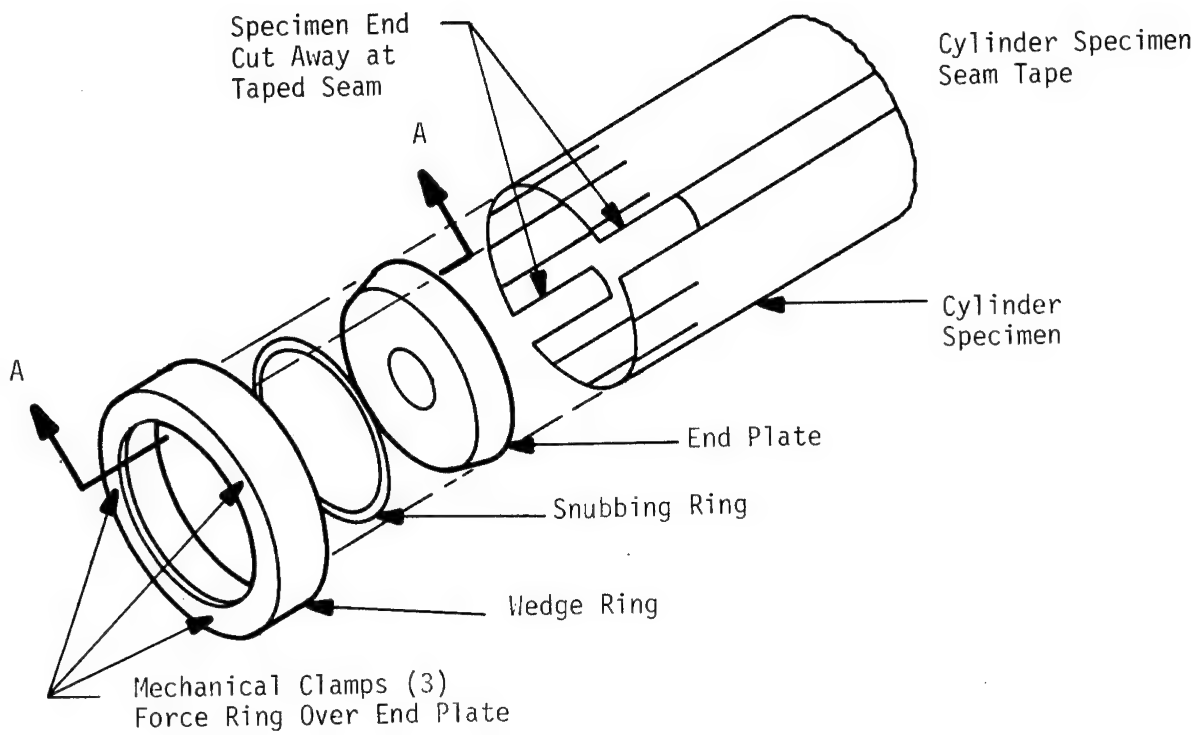
- T126600 Tape - Consists of 1000 denier, type 68 Dacron yarns 8/cm (20/in.) aligned transverse to the tape axis and bonded to a 51 g/m^2 (1.5 oz/yd^2) plain-weave nylon fabric with 50 μm (2 mils) of polyester base thermoset adhesive. 250 μm (10 mils) of polyester, thermoset adhesive are applied to the Dacron side.
- T126700 Tape - Consists of 38 μm (1.5 mil) Tedlar PVF film coated with 100 μm (4 mils) of polyester base thermoset adhesive.
- D048700 Tape - Consists of 95 g/m^2 (2.8 oz/yd^2) plain weave nylon fabric with 51 g/m^2 (1.5 oz/yd^2) aluminized Hypalon bonded to one side with 34 g/m^2 (1.0 oz/yd^2) of neoprene. The opposite side has 34 g/m^2 (1.0 oz/yd^2) of uncured neoprene suitable for solvent activation.
- "Coated Kevlar Laminate" - Consists of the 1-ply experimental, Kevlar laminate with 250 μm (10 mils) of polyester base, thermoset adhesive applied to the fabric side.

Figure 15. Seam Construction for Cylinder Test Specimens



(a) Initial Mounting (b) End Preparation Prior to Clamping (c) Mounting Complete

Figure 16. Cylinder Mounting—First Test Series



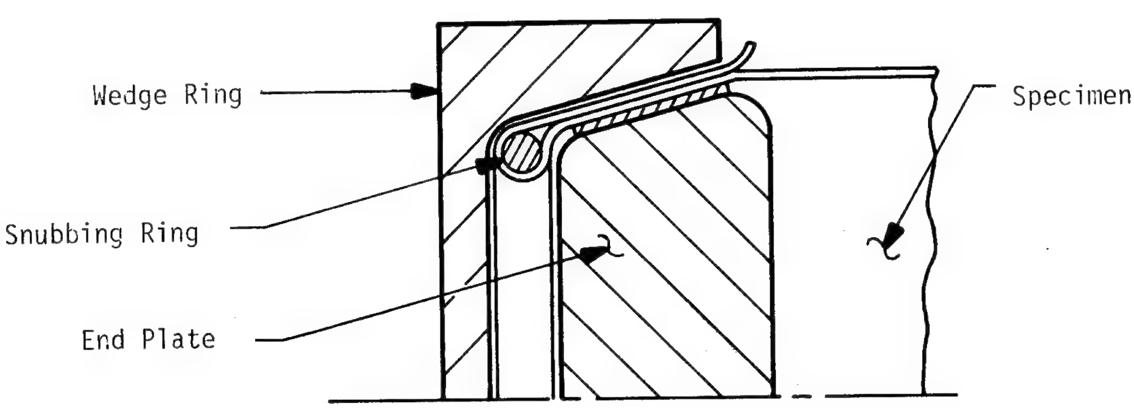
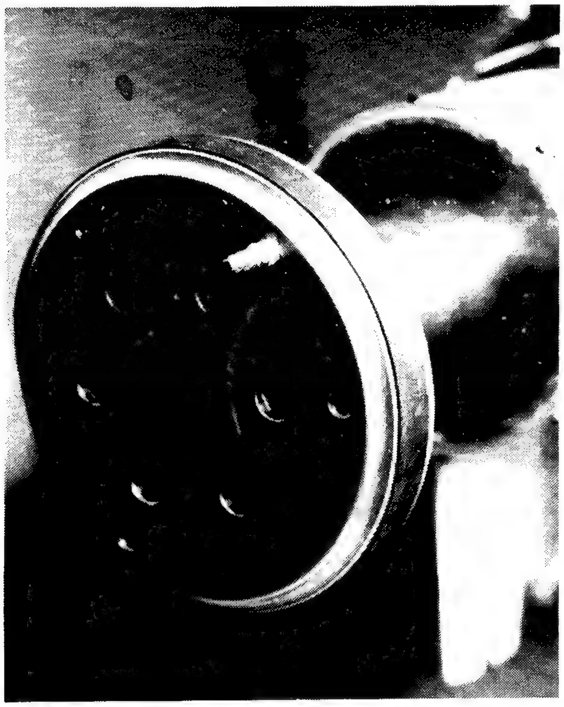
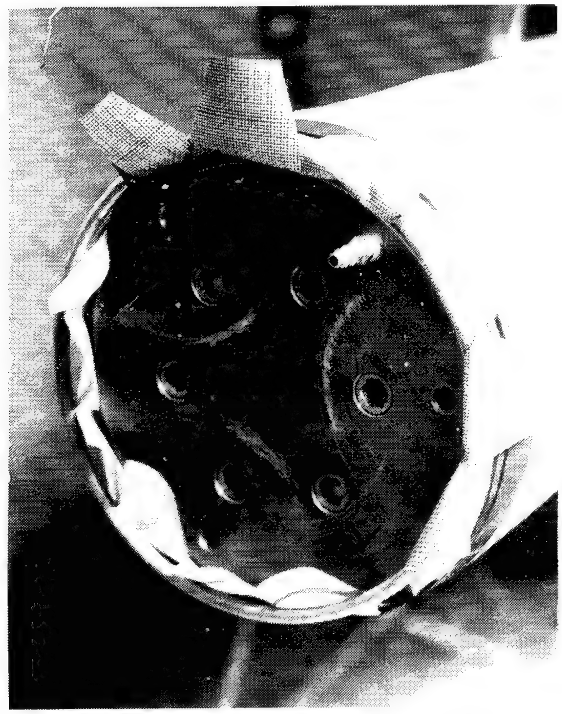


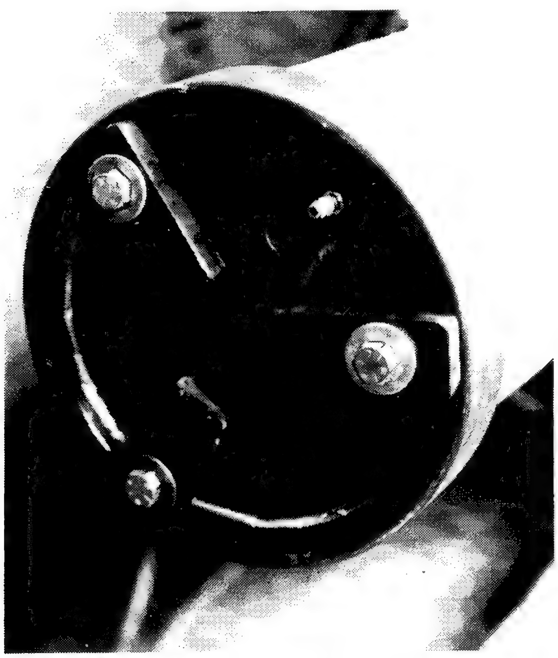
Figure 17. Cylinder Test Fixture - Modified Clamp
—Series 2 Tests



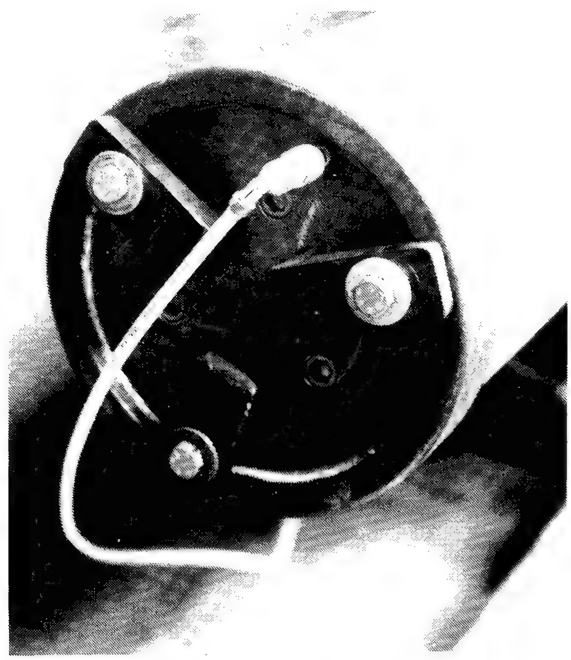
(a) Bare End Plate



(b) Specimen and Snubbing Ring in Place

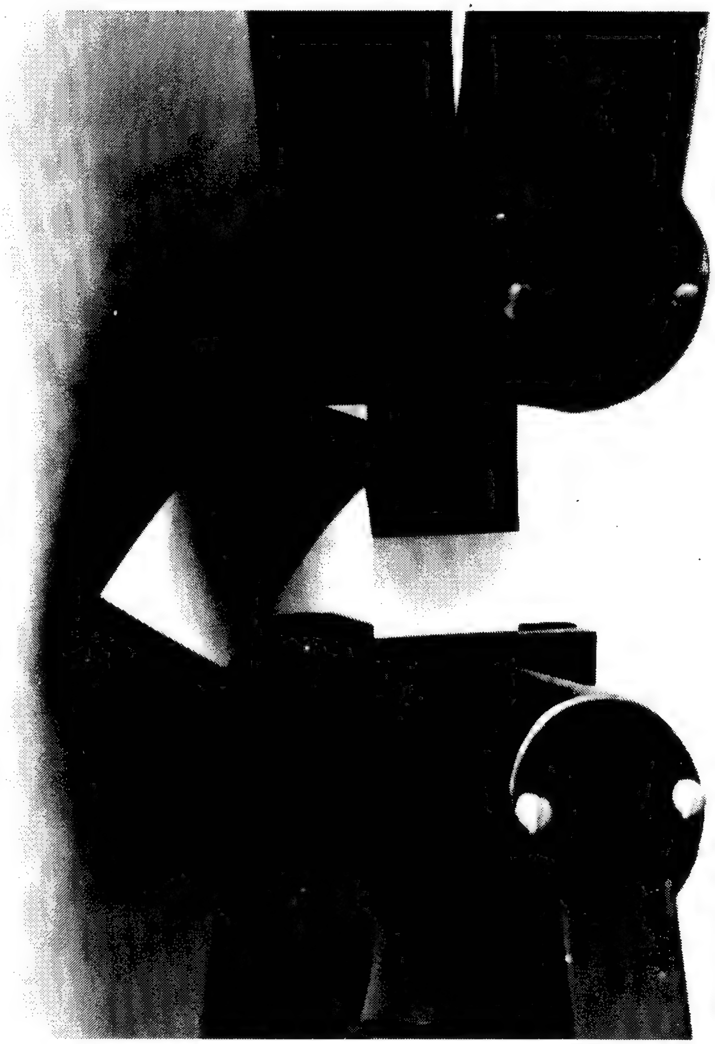


(c) Wedge Ring and Clamp Dogs in Place

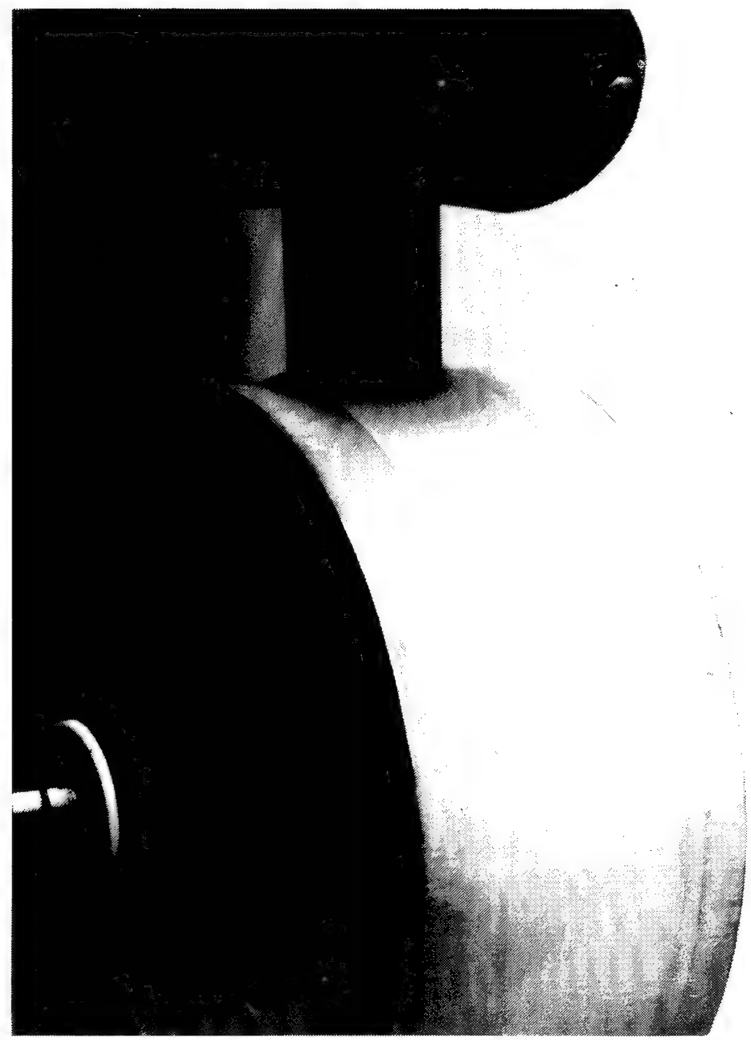


(d) Specimen Loaded Cyclically and Clamps Adjusted

Figure 18. Sequence for Mounting Cylinder Specimens to End Plates —Series 2 Tests

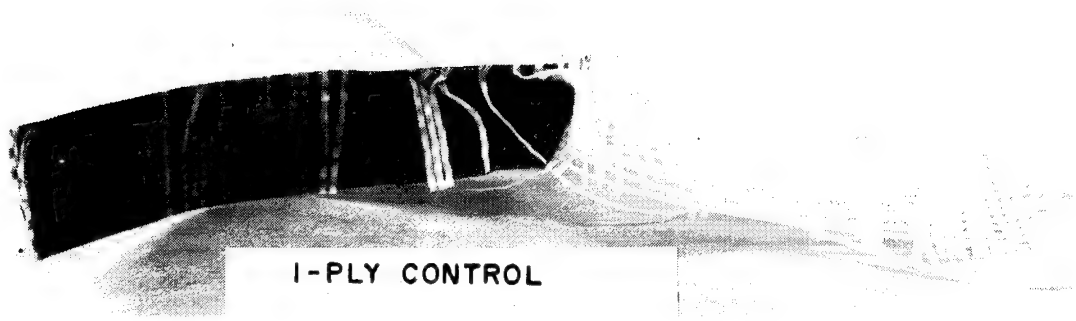


(a) ASTM-D-1876

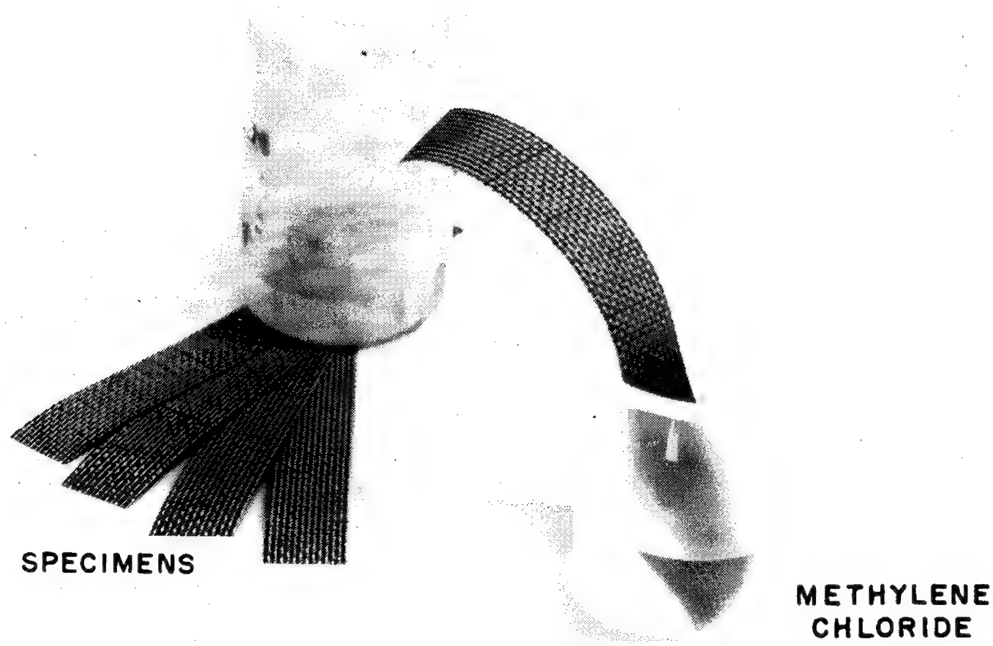


(b) Q-66 Method A

Figure 19. Peel Testing



(a) Tested Specimens



(b) Sample Preparation

Figure 20. Bond Strength Testing

Durability Tests

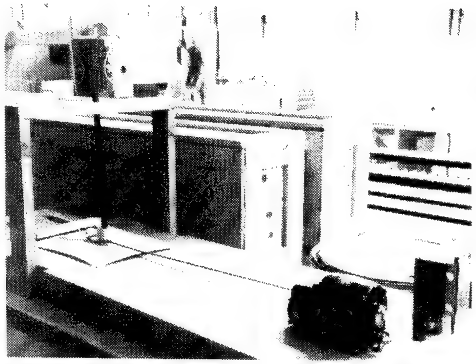
The experimental and control materials were exposed to wear and durability tests to measure characteristics essential to the performance of inflatable structures. These included measurement of crease, blocking, tear, abrasion and flex effects.

Crease effects. — Coupon samples were cut and accordion folded parallel to the grips with a 2.54 cm (1.0 in.) spacing between folds. The fold was a full 180° sharp crease. The coupons were tested per Federal Test Method 5102, like the uniaxial tensile tests to determine the loss in strength. Five samples were tested for each material at 22°C (72°F).

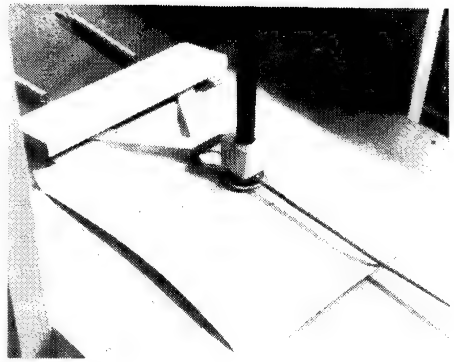
Blocking test. — The test method is described in Specification Q000041, Appendix B. With this method a dead load of 89 N (20 lb) was applied to a sample of 5.1 cm x 20.3 cm (2.0 in. x 8.0 in.) folded into a 5.1 cm x 5.1 cm (2.0 in. x 2.0 in.) square. The load is applied for 24 hours at 71°C (160°F), and the force required to separate the layers is determined. Five sample specimens were investigated for each of the two laminate materials since the coating materials used in the 2-ply materials do not exhibit measurable blocking effects.

Abrasion test. — Abrasion tests were conducted to determine the effect of wear produced when an inflatable structure is packaged and transported in the deflated state. The method employed uses a dead weight of 44.5 N (10 lb) acting on a 20 cm^2 (3.14 $in.^2$) circular pad which reciprocates against a horizontal plate at 60 strokes per minute, Figure 21. For each test, one piece of the test fabric was secured to the pad and another about 30 cm^2 (1 ft^2) was secured to the horizontal plate so that two identical surfaces were rubbed together. Laminate materials were tested Tedlar-to-Tedlar and coated materials Hypalon-to-Hypalon. Wear failure was assumed to have occurred when specimens were worn down to the fabric. One sample of each material was tested at ambient conditions. Typical sample appearance after failure and test record forms are illustrated in Figure 21.

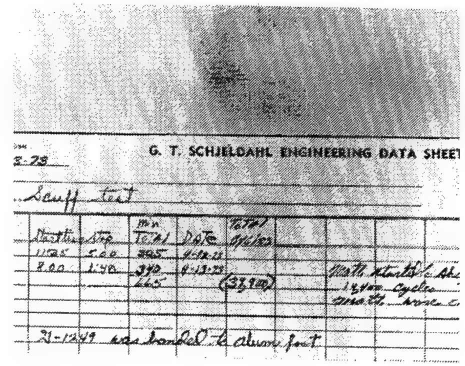
Trapezoidal tear tests. — Federal Test Method 5136 was employed in these tests. Sample form is a right trapezoid, 7.6 cm (3 in.) high with bases of 2.5 cm (1 in.) and 10.2 cm (4 in.) as shown in Figure 22(b). The test specimen is notched on the 2.5 cm (1 in.) base and clamped with the two non-parallel edges gripped in the jaws as shown in Figure 22(a). Grip separation rate was 30.5 cm/min (12 in./min). Five specimens of each material were tested at a temperature of 22°C (72°F). A standard trapezoidal template is shown in Figure 22(b) along with a cut sample and a tested and torn sample. The tear is normal to the warp yarns and generally a minimum tear force is noted along orthogonal tears. Bias tears require much higher tear forces. Loose uncoated weaves show greater tear strength than impregnated and coated and/or close weave materials. These features allow the fabricator to design for improved tear characteristics.



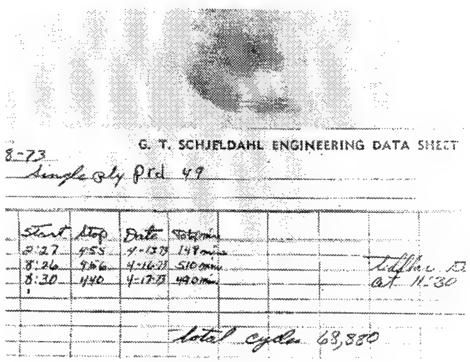
(a) Test Set-Up



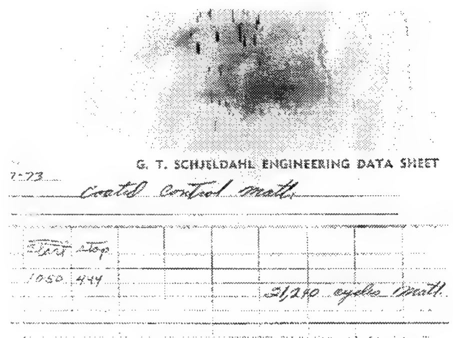
(b) Specimen During Test



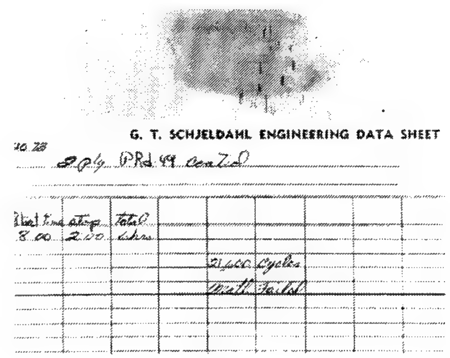
(c) Single-Ply Control Specimen



(d) Single-Ply Experimental Specimen

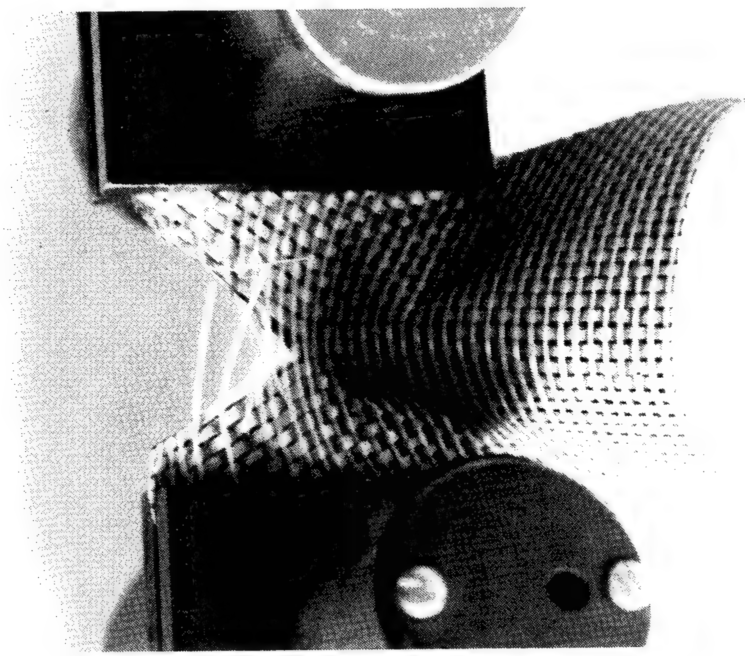


(e) Two-Ply Control Specimen

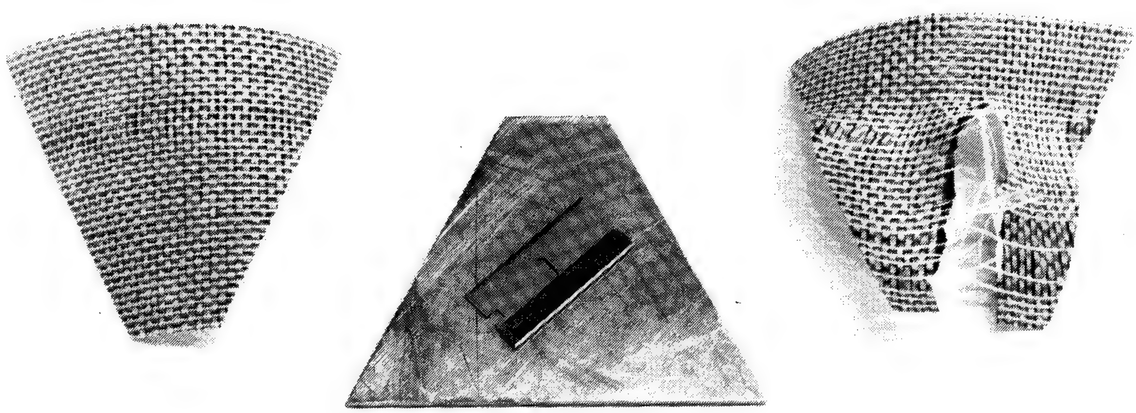


(f) Two-Ply Experimental Specimen

Figure 21. Abrasion Testing



(a) Specimen Under Test



(b) Test Specimens - Before and After Testing

Figure 22. Trapezoidal Tear Testing

Flex tests. — Flex tests were conducted on a Bally Flexometer, Figure 23(a). Rectangular fabric specimens 7.0 x 4.5 cm (2.8 x 1.8 in.) were folded in half parallel to the shorter dimension, then folded in half again at right angles, Figure 23(b) and (d). Warp yarns were aligned with the 7.0 cm dimension. Diagonally opposite from the double folded corner, the inner two free corners are secured to one clamp and the outer two corners to another clamp. During the test, one clamp reciprocates alternately toward and away from the other, causing the specimen to be flexed in the vicinity of the double fold at 100 cycles per minute. One specimen of each material type was tested to determine the number of cycles to failure in simulation of the effect of turbulent air flow over a balloon envelope and handling.

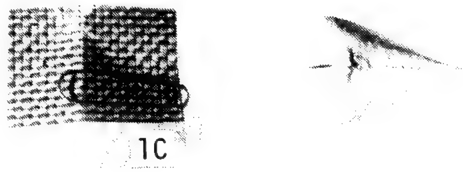
Geometric Properties

Composite weight and permeability depend on the geometry and constituency of the lamina.

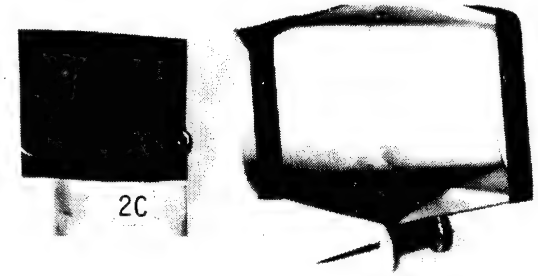
Weight measurements. — Weight measurements were made by cutting a 15.2 cm x 15.2 cm (6 in. x 6 in.) sample of each material and weighing it on a laboratory balance. For the conventional laminate material another weight parameter was measured. Since the fabric is a relatively loose weave, a weave set compound was added to afford dimensional stability. A sample of the material was cut and weighed as above, then boiled in two liters of water for an hour and weighed again after drying to determine the amount of weave set (see Figure 24).

Helium permeability tests. — Federal Test Method 5460 was used for the helium permeability tests. The unit of measure is liters of helium permeated per m^2 of material in 24 hours. Sample size was a 14.0 cm (5.5 in.) diameter circle of material. Three sample specimens of each material were tested at 27°C (72°F). All permeability tests were performed on virgin, uncreased and unstressed material samples.

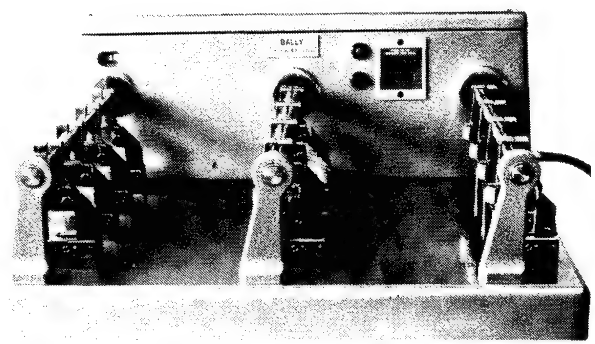
The edges of the circular specimen shown in the foreground of Figure 25 were coated with a soft wax and clamped between the hinged circular plates shown at the left. Helium introduced through the lower plate diffused through the specimen and its concentration between the specimen and upper plate is sensed by an analysis cell connected to the galvanometer through a Wheatstone bridge. Two readings taken at fixed time intervals establish the permeation rate per unit area.



(b) Single-Ply Control Specimens

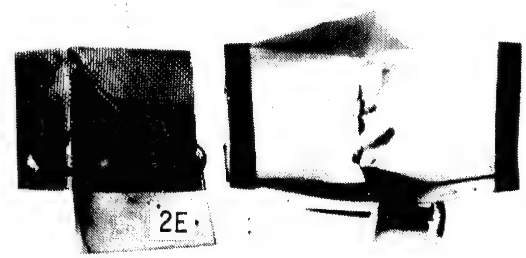


(c) Two-Ply Control Specimens



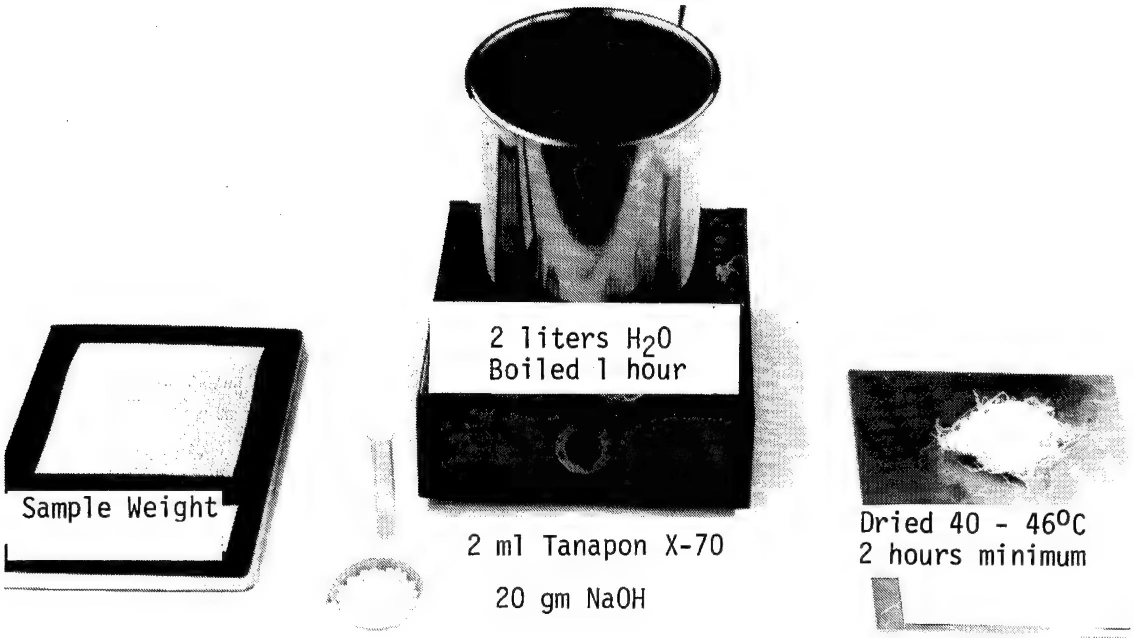
(a) Bally Flexometer

(d) Single-Ply Experimental

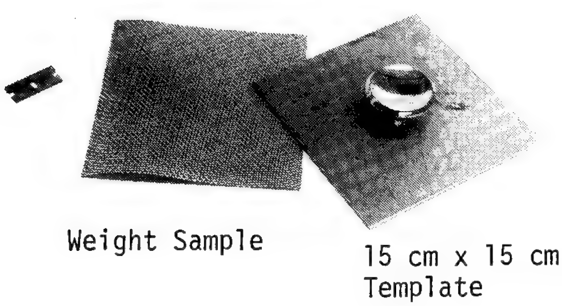


(e) Two-Ply Experimental Specimens

Figure 23. Flex Testing



(a) Weave Set (Sizing) Test Apparatus



(b) Sample Template and Preparation

(c) Laboratory Balance

Figure 24. Weight Measurement

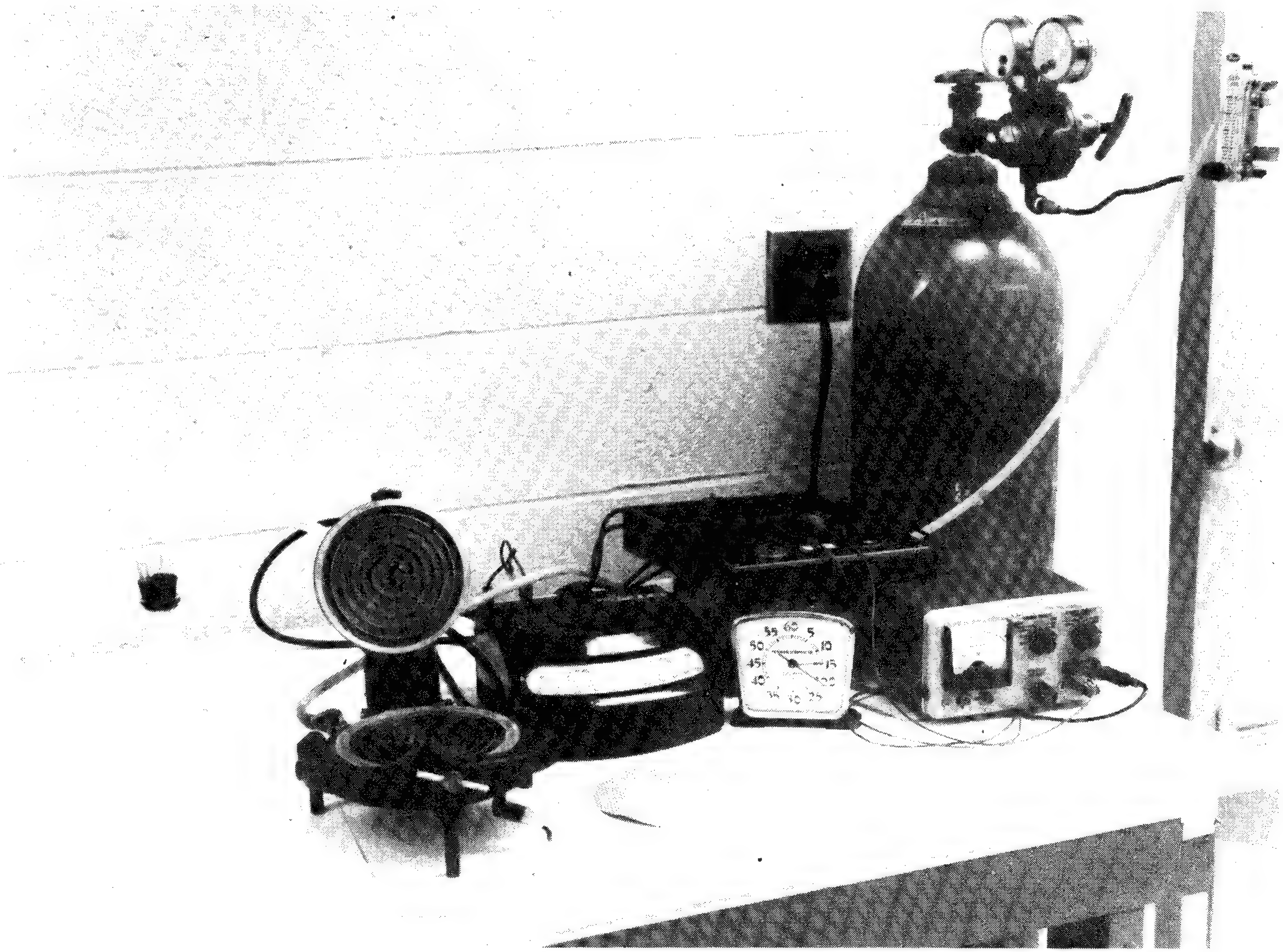


Figure 25. Permeability Test Apparatus

TEST RESULTS AND DISCUSSION

Strength test data have been obtained by uniaxial and biaxial testing and by peel tests. Durability test data are available from crease, abrasion, blocking, tear and flex tests. Geometric test data are furnished on helium permeability and constituent weights.

Strength Test Results

As noted on page 19, coupon testing of composites may yield questionable data because of the inability to fully involve yarns inclined at angles to the test direction. Considerable differences in test results were found for fabric-based materials when tested biaxially and when tested uniaxially.

Uniaxial tensile data. — Averages of uniaxial test data for tensile strength and elongation in both machine and transverse directions are shown for the four materials and the three test temperatures in TABLE 2 and Figure 26.

As expected, the data show that tensile values increase as temperature decreases and elongations vary inversely with the tensile strength. The clamping technique used for the laminate materials had to be changed at the -51°C (-60°F) conditon since excessive slippage in the jaws produced unequal filament loading and premature specimen failure. Fiber slippage was reduced to a minimum by snubbing the specimen ends in a pair of "D" shaped rings in place of the clamp-type grips. The effect was not observed with the coated materials, apparently because the yarns are held more firmly in the coating and little slippage occurs in the jaws.

Biaxial tensile data. — A considerable number of cylinder specimens was expended without obtaining valid, ultimate strength data because of difficulties with the apparatus and with individual specimens. Replacement and retesting of these within available funds was precluded by:

- The limited amount of sample materials available;
- The relatively large amount of material, 1.5 m^2 (16 ft^2), required for each specimen; and
- The considerable effort required (compared with other test methods) for specimen preparation, testing and data reduction.

Several specimens developed localized cracks at low load levels which prevented further internal pressurization. Attempts to repair these were usually unsuccessful because of additional specimen damage which occurred during removal from the test fixture. For some specimens, ultimate strength data were lost because of recorder or transducer malfunctions.

None of the materials could be made to fail under shear loading when the hoop load P_x was only one-third and the axial load P_y was one-sixth of their ultimate values. Instead, specimens would buckle into a pattern of helical wrinkles when (apparently) one of the principle membrane forces was reduced

TABLE 2

UNIAXIAL TEST DATA SUMMARY

(Average Tensile Values, N/m (lb/in.)

TEST TEMPERATURE °C	1 Ply Control		2 Ply Control		1 Ply Exp.		2 Ply Exp.	
	MD	TD	MD	TD	MD	TD	MD	TD
60°C (140°F)	40,250 (230)	38,500 (220)	30,275 (173)	25,900 (148)	44,975 (257)	52,500 (300)	57,925 (331)	53,025 (303)
22°C (72°F)	45,850 (262)	46,025 (263)	32,200 (184)	26,950 (154)	47,075 (269)	57,750 (330)	68,950 (394)	73,500 (420)
-51°C (-60°F)	45,150 (258)	45,675 (261)	37,800 (216)	36,750 (210)	56,175 (321)	58,450 (334)	80,500 (460)	79,975 (457)

Average Percent Elongation at Break								
60°C (140°F)	25.0	40.0	29.0	32.0	14.0	6.0	10.0	9.0
22°C (72°F)	24.0	40.0	27.0	29.0	13.0	6.0	9.0	7.0
-51°C (-60°F)	12.0	29.0	18.0	23.0	5.0	6.0	8.0	6.0

MD = Machine Direction
TD = Transverse Direction

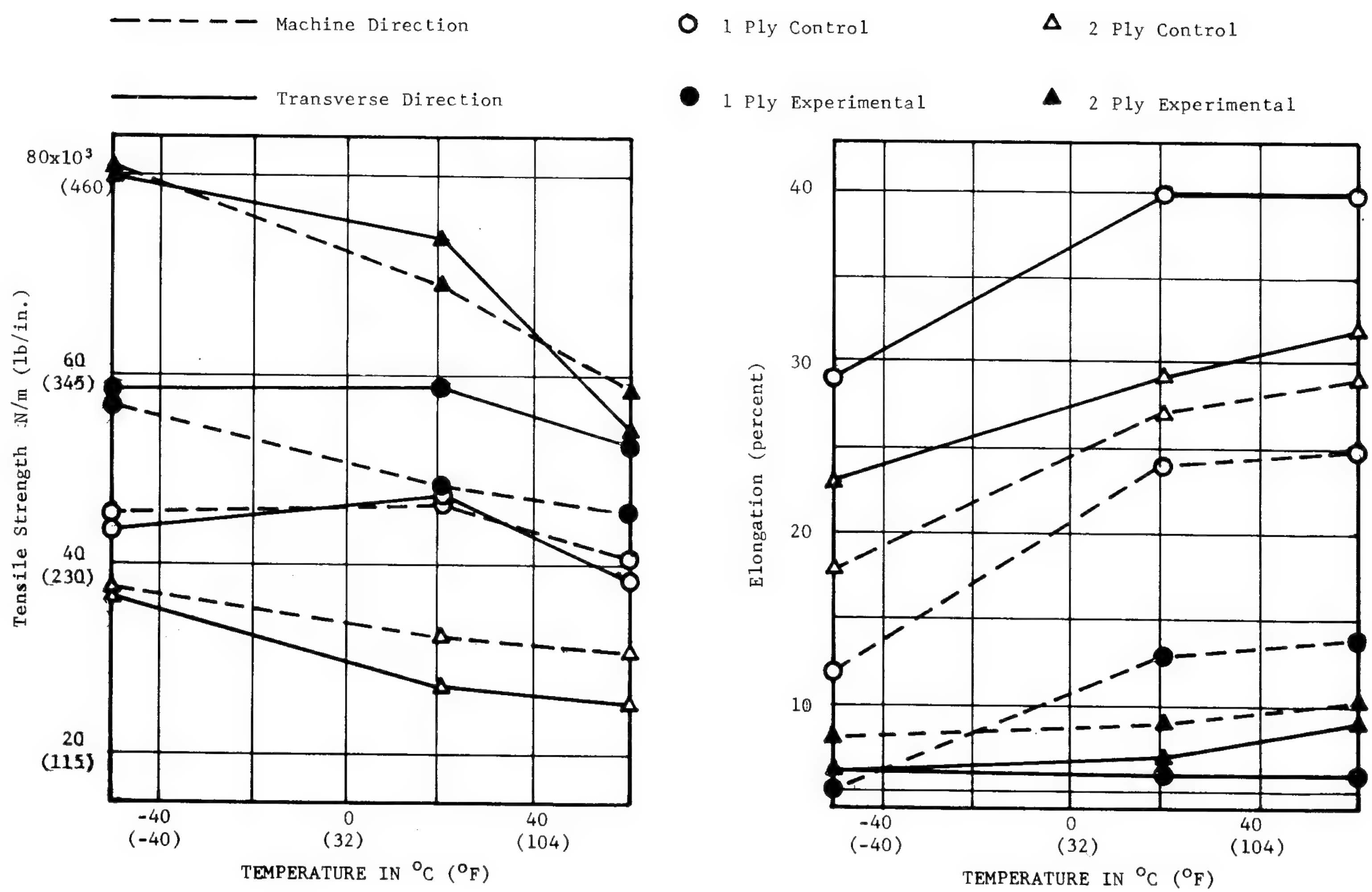


Figure 26. Variation of Ultimate Uniaxial Tensile Strength and Elongation with Temperature

to zero as the specimen was twisted. The onset of buckling was generally accompanied by a discontinuity in the trace of axial strain with time caused by an abrupt reduction in the distance between end clamps. A few specimens failed in shear at or near this buckling boundary at a temperature of -50°C when P_x was 40 percent and P_y was 20 percent of ultimate. Cylinder failure data obtained for specimens under combined load and shear were insufficient to serve as a basis for comparing materials.

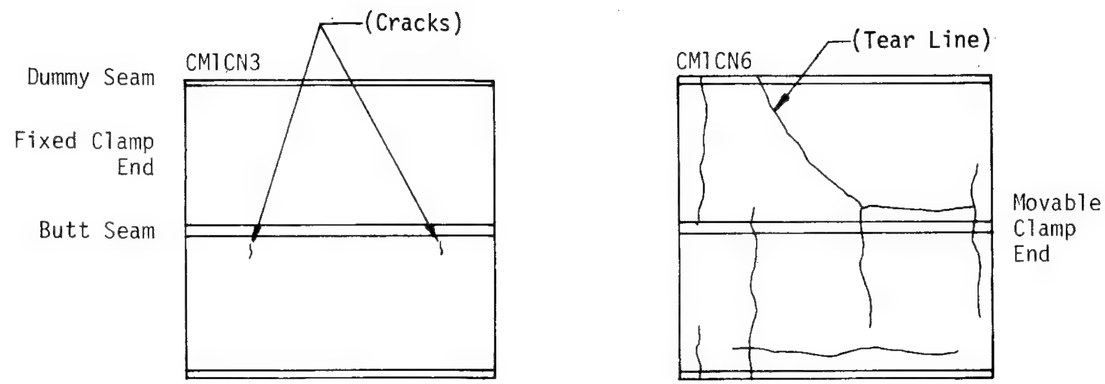
On Figures 27 and 28 numerical test results are tabulated for nine specimens each of the four test materials. Also 15 failure maps are included for those specimens experiencing damage. Only three specimens each of the four materials had applied shear loads and none of these were tested to damaging levels. The location of cracks and tears are mapped on rectangles representing specimens opened along dummy seams and laid flat. The data include results from tests terminated by apparatus failure, specimen leaks and similar test pecularities as well as results from specimens which ruptured catastrophically. Maximum strains and initial elastic data are listed in the tables along with the membrane forces. Table symbols denote the following:

$\sigma_H t$ = Hoop membrane force, P_x, (N/m)
ε_H = Hoop elongation (m/m)
$E_H t$ = Elastic stiffness in the hoop (machine, warp) direction (N/m)
$\sigma_A t$ = Axial membrane force, P_y, (N/m)
ε_A = Axial elongation (m/m)
$E_A t$ = Elastic stiffness in the axial (transverse, fill) direction (N/m)
τ_t = Shear membrane froce, P_{xy}, (N/m)
ε_τ = Shear elongation (m/m)
$E_\tau t$ = Shear stiffness (N/m)

Letters in parentheses refer to the following notes:

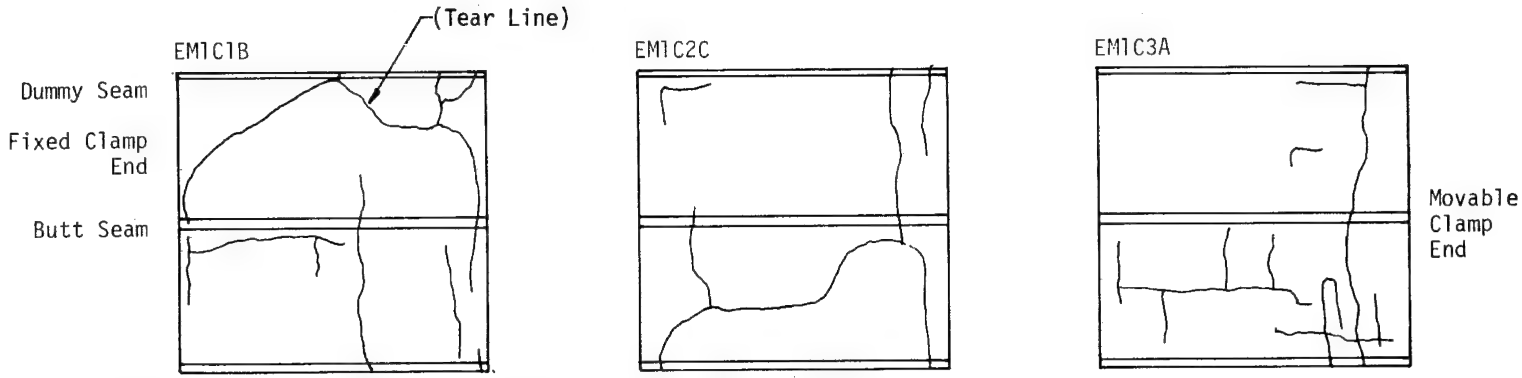
(a) Data at P_x = 1/3 ultimate uniaxial breaking strength
(b) Data at buckling boundary
(c) Not a failure point
(d) Data not recorded
(e) Sample failed
(f) All (Et) data in units of 1×10^5 N/m
(g) Insufficient data

On Figures 27 and 28 only two of those damaged specimens of the 12 control material tests without shear (P_{xy} = 0) resulted in general specimen rupture. The one-ply control specimen (CM1CN6) and the two-ply control (CM2CN6) that failed were the only control materials loaded to their ultimate capacities. The one-ply control failed at a load which is comparable to its experimental counterpart. The two-ply control failed at about one-third the capacity of its experimental counterpart. These results are reasonable and consistent with design goals.

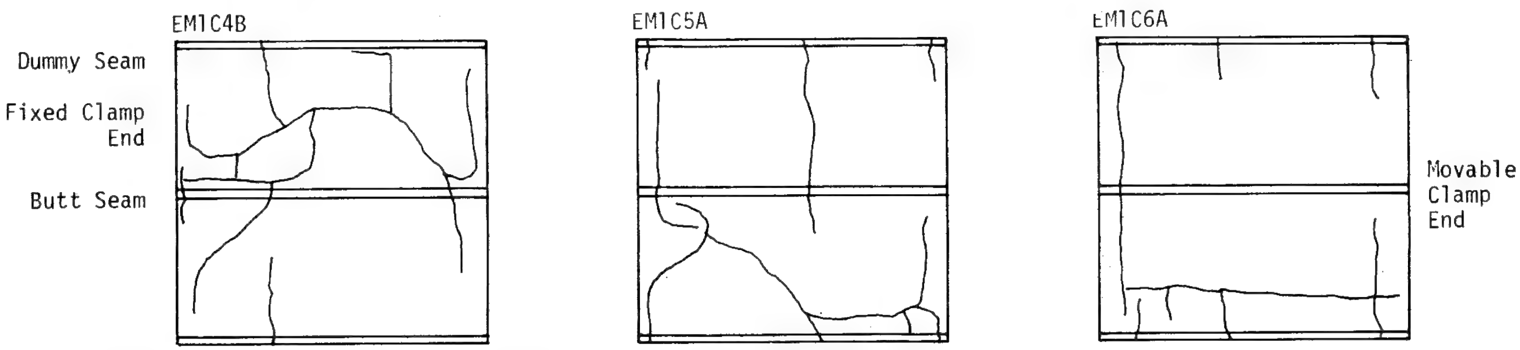


	Sample No.	Test Temp. (°C)	$\sigma_H t$	ε_H	$E_H t$ (a,f)	$\sigma_A t$	ε_A	$E_A t$ (a,f)	τt	ε_τ	$E_\tau t$ (f)	P_x/P_y
			Hoop			Axial			Shear (b)			
(c)	CM1CN1	-51.	9084.	0.0017	(g)	9413.	0.0127	(g)	0.	0.	0.	1.0
(c)	CM1CN2	22.	7962.	0.0087	(g)	9117.	0.0249	(g)	0.	0.	0.	1.0
(c)	CM1CN3	60.	13009.	(d)	ND	14939.	0.0706	(g)	0.	0.	0.	1.0
(c)	CM1CN4	-51.	9925.	0.0036	(g)	6121.	0.0038	(g)	0.	0.	0.	2.0
(c)	CM1CN5	22.	12168.	0.0296	(g)	7402.	0.0141	(g)	0.	0.	0.	2.0
(e)	CM1CN6	60.	33194	(d)	N.D.	17029.	0.0691	1.80	0.	0.	0.	2.0
	CM1CN7	-51.	12168.	0.0140	--	7402.	0.0070	--	5113.	0.0698	0.21	2.0
	CM1CN8	22.	12168	0.0268	--	6942.	0.0188	--	3568.	0.1147	0.12	2.0
	CM1CN9	60.	13569.	0.0386	--	8059.	0.0179	--	3662.	0.1463	0.16	2.0

Figure 27(a). Representative Biaxial Test Results for One-Ply Control Material

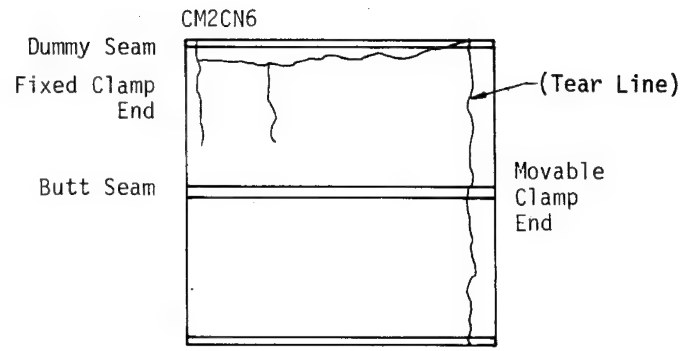


EM1C1B	-51.	32353.	0.0290	7.90	32993.	0.0294	8.30	0.	0.	0.	1.0
EM1C2C	22.	30110.	0.0358	8.19	29868.	0.0283	7.89	0.	0.	0.	1.0
EM1C3A	60.	31792.	0.0182	9.26	32039.	0.0290	7.61	0.	0.	0.	1.0



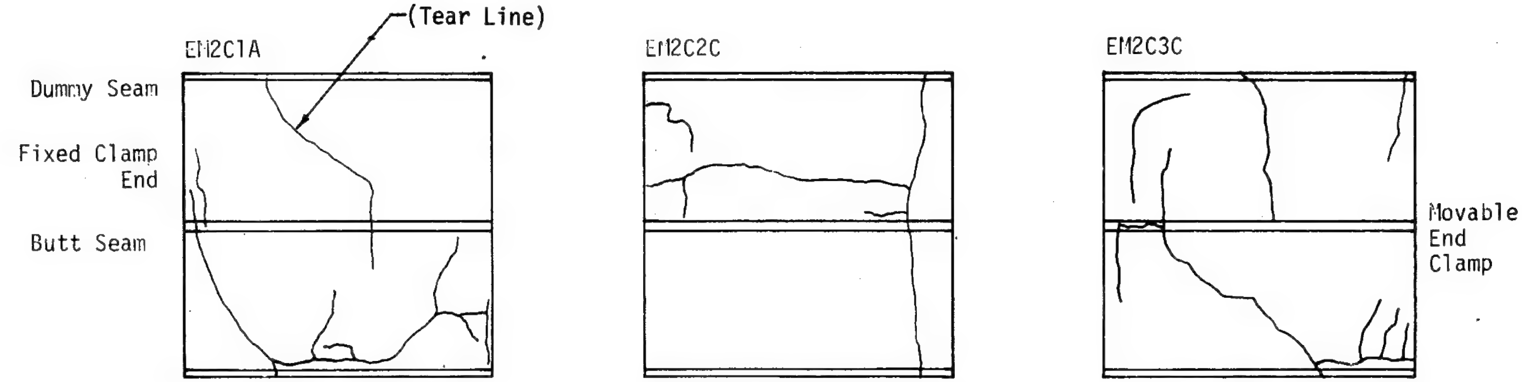
Sample No.	Test Temp. (^oC)	$\sigma_H t$ (Hoop)	ε_H (Hoop)	$E_H t$ (a,f) (Hoop)	$\sigma_A t$ (Axial)	ε_A (Axial)	$E_A t$ (a,f) (Axial)	τt (Shear (b))	ε_τ (Shear (b))	$E_\tau t$ (f) (Shear (b))	P_x/P_y
EM1C4B	-51.	35997.	0.0306	8.41	18343.	0.0083	19.9	0.	0.	0.	2.0
EM1C5A	22.	35437.	0.0335	5.87	18080.	0.0097	22.1	0.	0.	0.	2.0
EM1C6A	60.	33474.	0.0357	5.93	17391.	0.0071	32.7	0.	0.	0.	2.0
EM1C7B	-51.	14691.	0.0044	--	8124.	0.0017	--	4411.	0.0526	0.25	2.0
EM1C8A	22.	10766.	0.0228	--	5824.	0.0037	--	2024.	0.0516	0.21	2.0
EM1C9A	60.	11607.	0.0112	--	5987.	0.0041	--	2258.	0.0660	0.19	2.0

Figure 27(b). Representative Biaxial Test Results for One-Ply Experimental Material

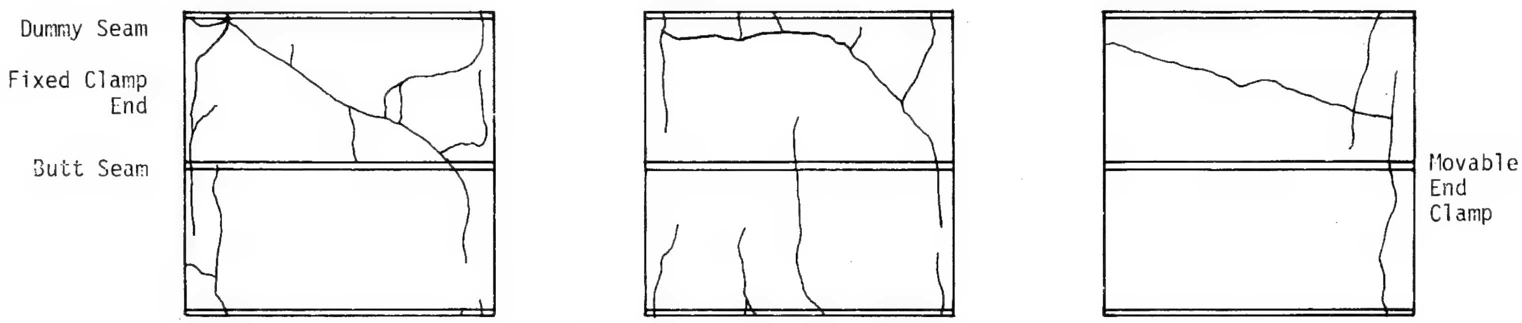


	Sample No.	Test Temp. (^oC)	$\sigma_H t$	ε_H	$E_H t$ (a,f)	$\sigma_A t$	ε_A	$E_A t$ (a,f)	τt	ε_τ	$E_\tau t$ (f)	P_x/P_y
				Hoop			Axial			Shear (b)		
(c)	CM2CN1	-51.	7121.	0.0264	(g)	7341.	0.0044	(g)	0.	0.	0.	1.0
(c)	CM2CN2	22.	7402.	0.0450	(g)	7242.	0.0167	(g)	0.	0.	0.	1.0
(c)	CM2CN3	60.	9645.	0.0802	(g)	12901.	0.0938	(g)	0.	0.	0.	1.0
(c)	CM2CN4	-51.	8523.	0.0074	(g)	5463.	(d)	(g)	0.	0.	0.	2.0
(c)	CM2CN5	22.	8523.	0.0422	(g)	5694.	0.0018	(g)	0.	0.	0.	2.0
(e)	CM2CN6	60.	14691.	(d)	N.D.	8355.	0.0291	4.17	0.	0.	0.	2.0
	CM2CN7	-51.	9925.	0.0295	--	6121.	0.0045	--	6282.	0.1060	0.36	2.0
	CM2CN8	22.	10205.	0.0797	--	6482.	0.0089	--	5768.	0.2055	0.19	2.0
	CM2CN9	60.	10766.	0.0638	--	6515.	0.0320	--	4785.	0.0467	0.68	2.0

Figure 28(a). Representative Biaxial Test Results for Two-Ply Control Material



EM2C1A	-51.	38240.	0.0108	32.4	37827.	0.0328	8.45	0.	0.	0.	1.0
EM2C2C	22.	39362.	0.0132	14.0	39274.	0.0281	10.5	0.	0.	0.	1.0
EM2C3C	60.	43006.	0.0045	(g)	41454.	0.0278	9.64	0.	0.	0.	1.0



		Hoop			Axial			Shear (b)			
Sample No.	Test Temp. (°C)	$\sigma_H t$	ε_H	$E_H t$ (a,f)	$\sigma_A t$	ε_A	$E_A t$ (a,f)	τt	ε_τ	$E_\tau t$ (f)	P_x/P_y
EM2C4A	-51.	55622.	0.0245	20.5	27543.	0.0055	76.0	0.	0.	0.	2.0
EM2C5C	22.	53660.	0.0256	14.7	26393.	0.0073	83.9	0.	0.	0.	2.0
EM2C6A	60.	45810.	0.0165	14.6	22713.	0.0086	30.8	0.	0.	0.	2.0
EM2C7B	-51.	15532.	0.0006	--	8749.	0.0018	--	6095.	0.0669	0.30	2.0
EM2C8C	22.	14411.	0.0125	--	7532.	0.0022	--	3241.	0.0985	0.21	2.0
EM2C9C	60.	15812.	0.0018	--	8189.	0.0035	--	2773.	0.0832	0.22	2.0

Figure 28(b). Representative Biaxial Test Results for Two-Ply Experimental Material

The failure maps indicate the extensive tears that characterized specimen rupture for all four materials. Close examination of torn edges failed to indicate where a given tear might have originated. Generally, all ruptured specimens exhibited circumferential tears near the end clamps, particularly the movable clamp, and most had shorter axial tears near a seam. Specimens with $P_x/P_y = 2$ did not appear to have more tears transverse to the P_x force than specimens with $P_x/P_y = 1$.

Ultimate membrane forces, at $P_{xy} = 0$, for those cylinder specimens which burst catastrophically are plotted on the P_x - P_y plane in Figures 29 and 30. Individual uniaxial tensile data in warp and fill directions are plotted along the axes for comparison. It is concluced that the test data on both uniaxial and biaxial strengths are less than the true ultimate capacities of the materials as a consequence of test peculiars, namely:

- o Presence of seams — Axial cylinder seams introduce discontinuities in stiffness in the free length of the specimen and discontinuities in thickness in the end clamps.
- o Curved snubbing element — Axial yarns in cylinders will not be uniformly loaded when the (flat) fabric laminate at the ends is folded around the (torroidal) surface of the snubbing ring.
- o Hoop restraints — Load distribution near end clamps of cylinders will be nonuniform at the axial inflection between the radially restrained cylinder ends and the radially deformed center section.
- o Free edges — Free edges and the dimensions of the coupons prevent direct load transfer between clamps, through the bias ply of two-ply materials.

All of the above cause a downward bias in measured strength.

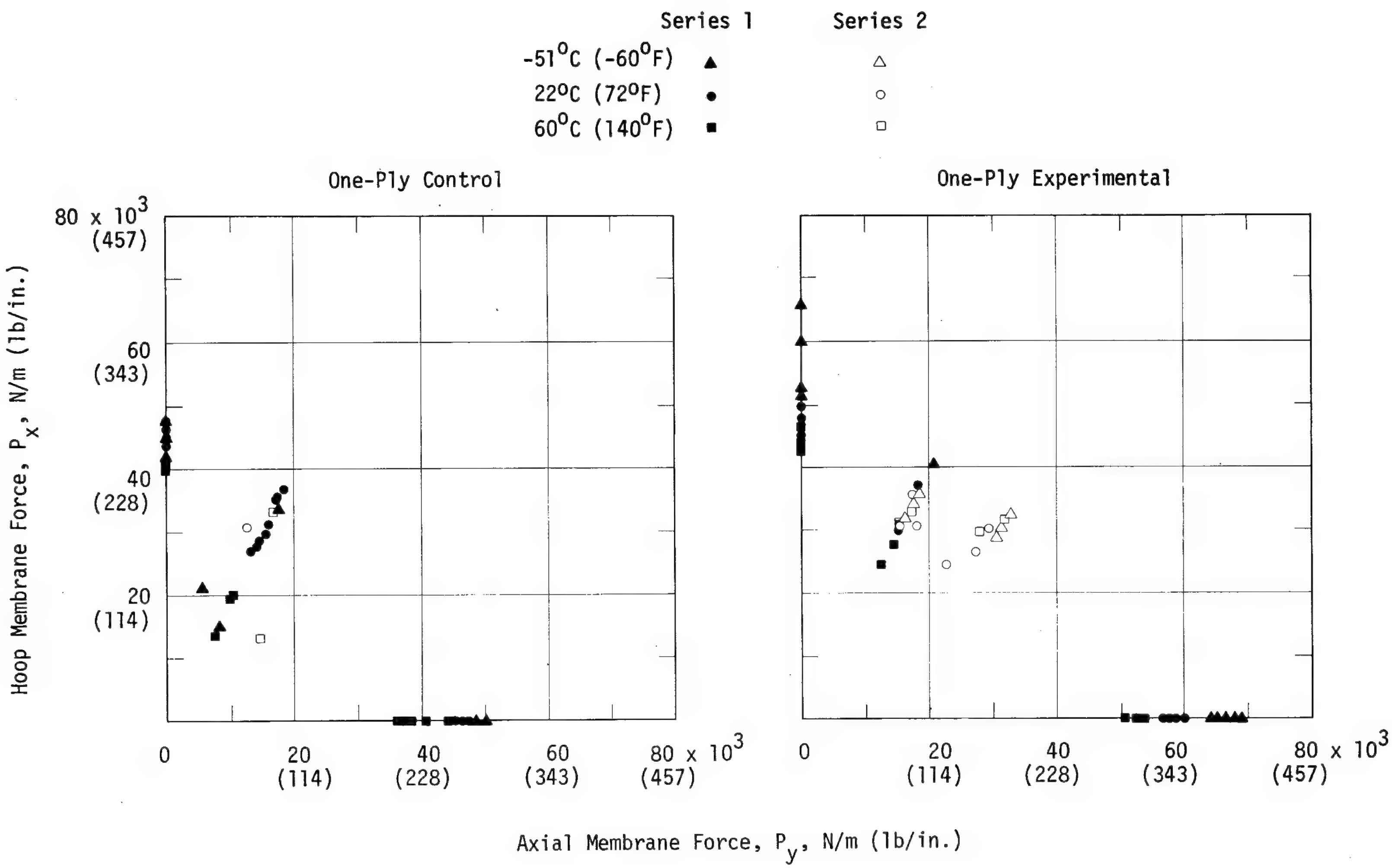


Figure 29. Failure Loads at Zero Shear for One-Ply Materials

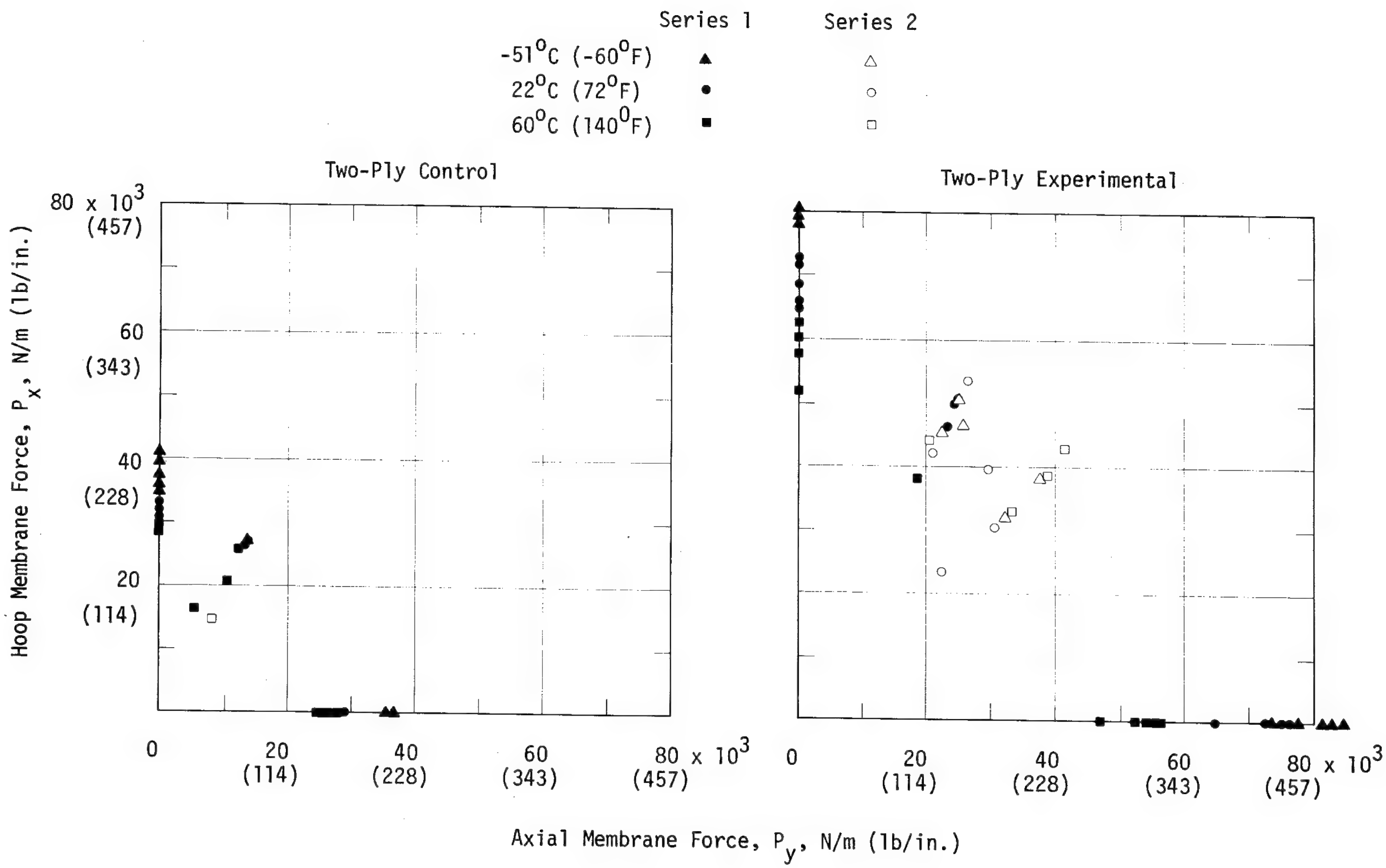


Figure 30. Failure Loads at Zero Shear for Two-Ply Materials

For each set of data in Figures 29 and 30 at the same temperature and P_x/P_y ratio, there is considerable dispersion about the mean value. Scatter in biaxial results appears to be about comparable to the scatter for uniaxial data. Scatter for uniaxial and biaxial results at -51°C is greater than at other temperatures. Differences between first and second series test data are generally less than the data spread for either series. The observed dispersions may be attributed to one or more of the following:

- Inherent variability in the material;
- Temperature variations over the specimen and between specimens (Figure 14);
- Localized slippage of material through the clamps, particularly near axial seams in cylinder specimens;
- Variations in alinement and position of material folds in the clamps of cylinder specimens;
- Interaction of the crimped warp and fill yarns in the fabric of specimens under combined loads.

The data of Figures 29 and 30 indicate that the goals set for the development of the one-ply laminate and the two-ply coated Kevlar materials were achieved. Evidently, the uniaxial and biaxial strengths for the one-ply experimental laminate are equal to or better than the one-ply control. This was achieved with a considerable reduction in weight, which was the prime objective. The two-ply experimental material in Figure 30 is shown to have gained about twice the biaxial strength of its control while maintaining a comparable weight, which was the objective for the two-ply experimental material.

Elastic characteristics. — Load-strain data acquired during the biaxial tensile tests were used to determine the biaxial elastic and shear stiffness coefficients.

To acquire a fixed, unstrained reference length it was necessary to seat the cylinder specimen in the clamps by applying repeated load cycles until the cylinder reference length stabilized. Figure 31 shows how axial strain becomes asymptotic to a constant strain after about six cycles of preloading. Friction in mechanical linkages of Figure 13 caused irregular and discontinuous motion and impaired accuracy at strains below 0.5 percent.

Force-displacement data are given in Figure 32 for the hoop and axial directions (material warp and fill directions) for $P_x/P_y = 1$, $P_{xy} = 0$, and various temperatures. Similar data for $P_x/P_y = 2$ and $P_{xy} = 0$ are given in Figure 33. Force-displacement curves for variable shear loading are given in Figure 34 for $P_x/P_y = 2$. In these figures, each line is from a single cylinder speciment test.

In Figure 35, elastic stiffness coefficients, Et, are shown for each material at various temperatures. These data were determined at 1/3 of the ultimate uniaxial breaking strength by measuring the slope of tangents to the curves at that point in Figures 32 and 33. Since the load-strain data for the control materials end at 1/3 of the ultimate uniaxial breaking strength, load-strain data from the first series of tests were used.

In Figures 32 and 33, the controls display the conventional stress-strain characteristics of diminishing stiffness with increasing stress (second order curve with negative curvature). The Kevlar experimental materials show initial, diminishing stiffness with a later recovery. This results in a third order curve with an inflection point and a positive terminal curvature. This terminal stiffening is attributed to the reduction in yarn crimp at high loads and the ensuing full mechanical action of the high modulus Kevlar filaments. Stiffness of the Kevlar materials varies by a factor of two, from zero to maximum load level. The non-linear load strain characteristic of the controls also resulted in load-dependent stiffness coefficients. The lack of positive inflection and stiffness recovery near terminal values for the controls is attributed to the smaller spread between the stiffness of the adhesives, coatings, films and the Dacron filaments.

The Kevlar composites display increased dimensional rigidity relative to the control materials as would be expected from the high modulus fibers. For example, the single-ply Kevlar laminate, in Figure 35, shows about four times the stiffness in the warp direction as the Dacron counterpart. The two-ply Kevlar material has about five times the stiffness of the corresponding Dacron two-ply. The high rigidity of the Kevlar composites is advantageous for many structural applications, but is a disadvantage in applications requiring folding and high density packaging.

Only limited data were acquired for the shear stiffness, $E_T t$. These data, tabulated in Figures 27 and 28 were calculated from the variable stress-strain measurements of Figure 34. The values of $E_T t$ apply only for P_x equal to 1/3 of ultimate and P_y equal to 1/6 of ultimate uniaxial load.

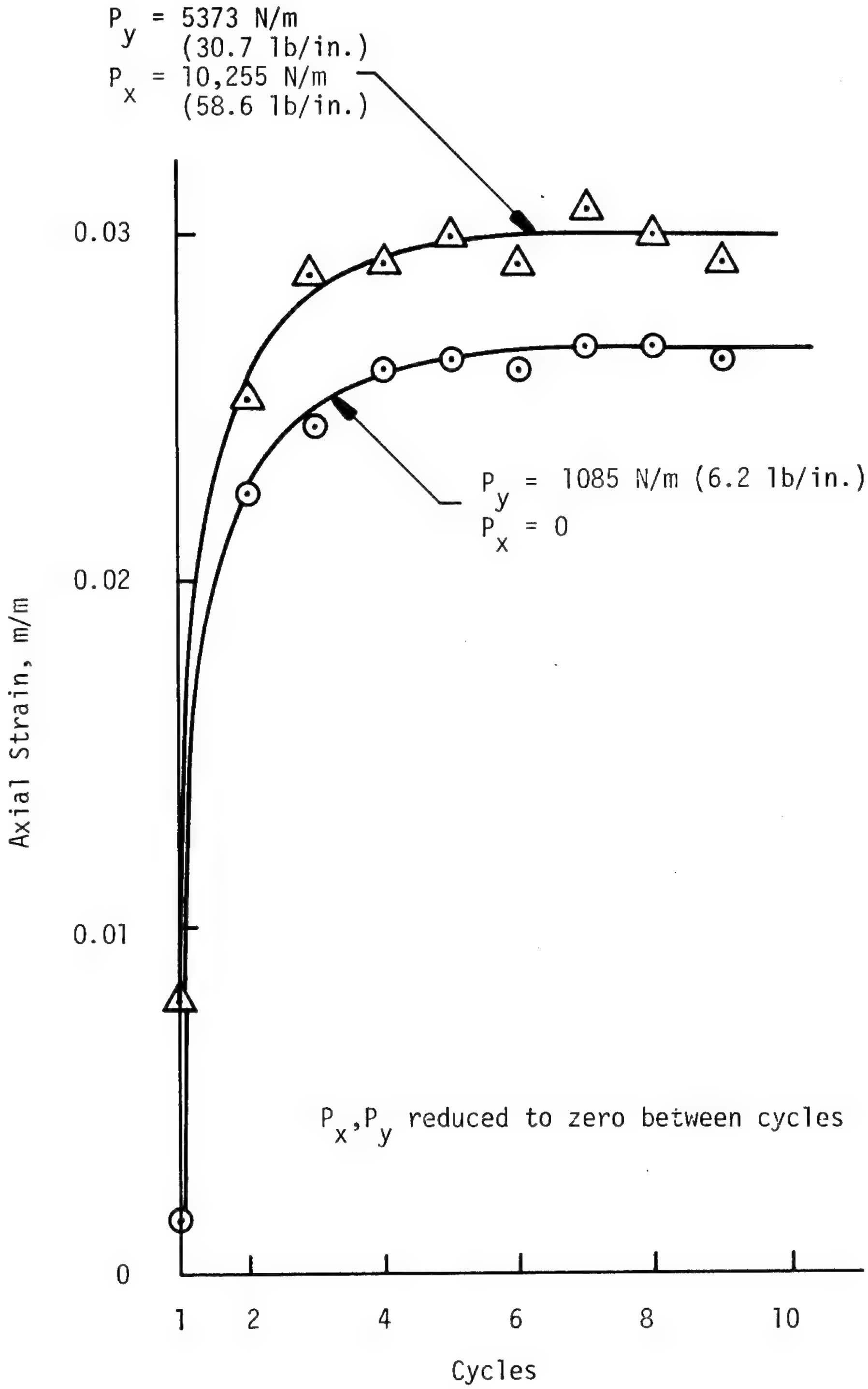


Figure 31. Effects of Cyclic Loading on Axial Strain of One-Ply Coated Material at 22°C

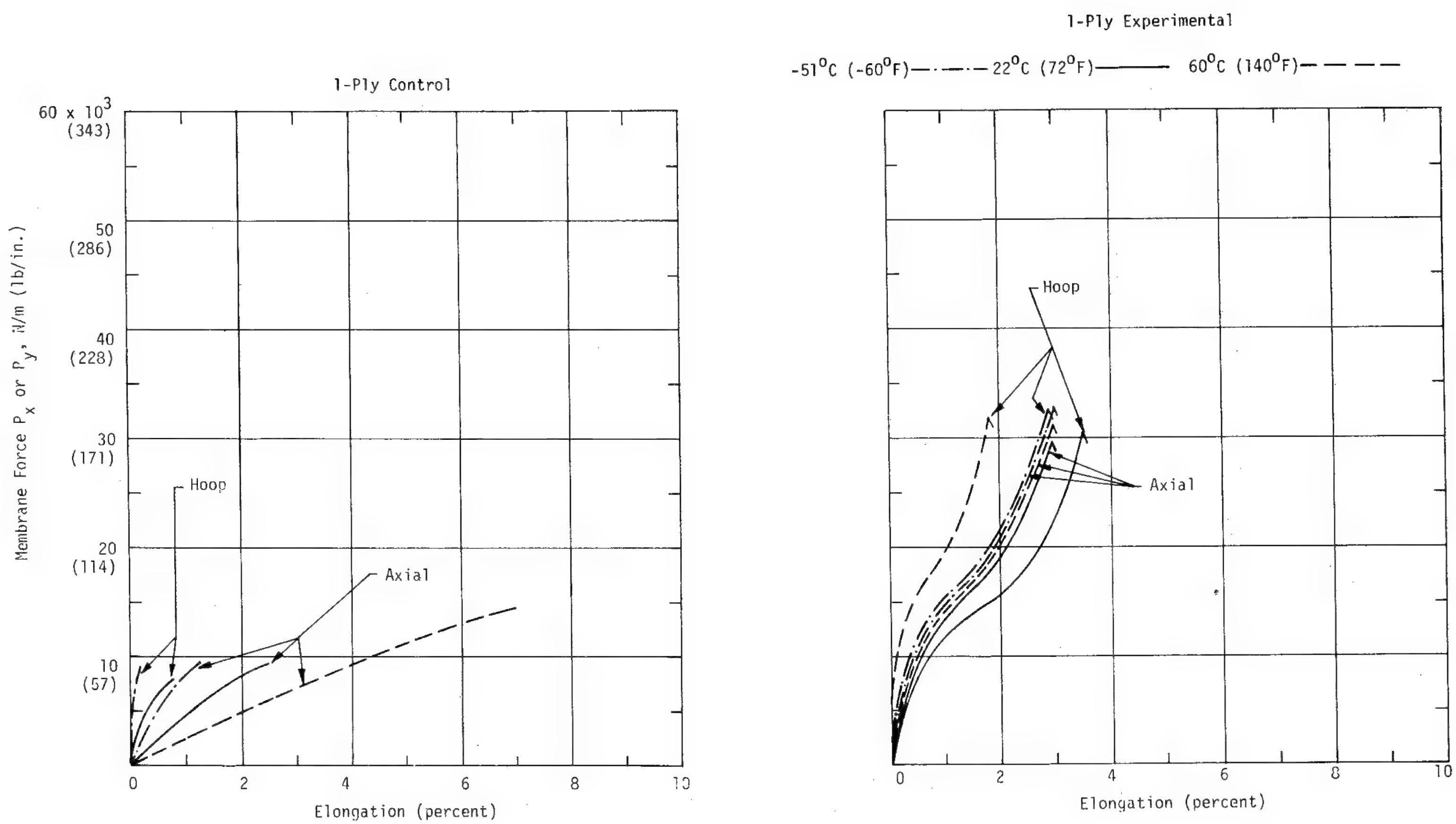


Figure 32. Stress-Strain Relations at Biaxial Stress Combination $P_x/P_y = 1$ and Zero Shear Load

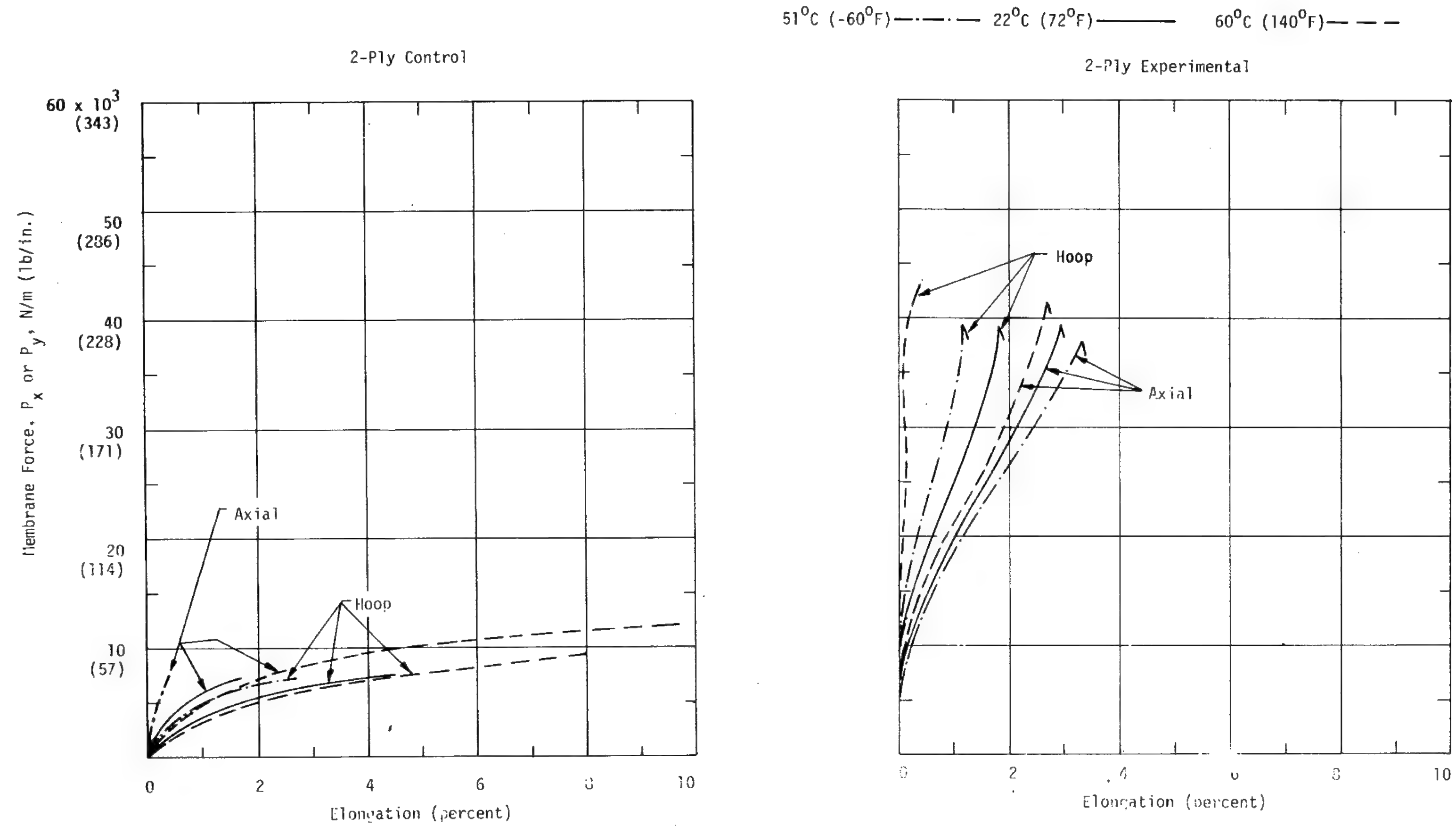


Figure 32. Stress-Strain Relations at Biaxial Stress Combination $P_x/P_y = 1$ and Zero Shear Load (Continued)

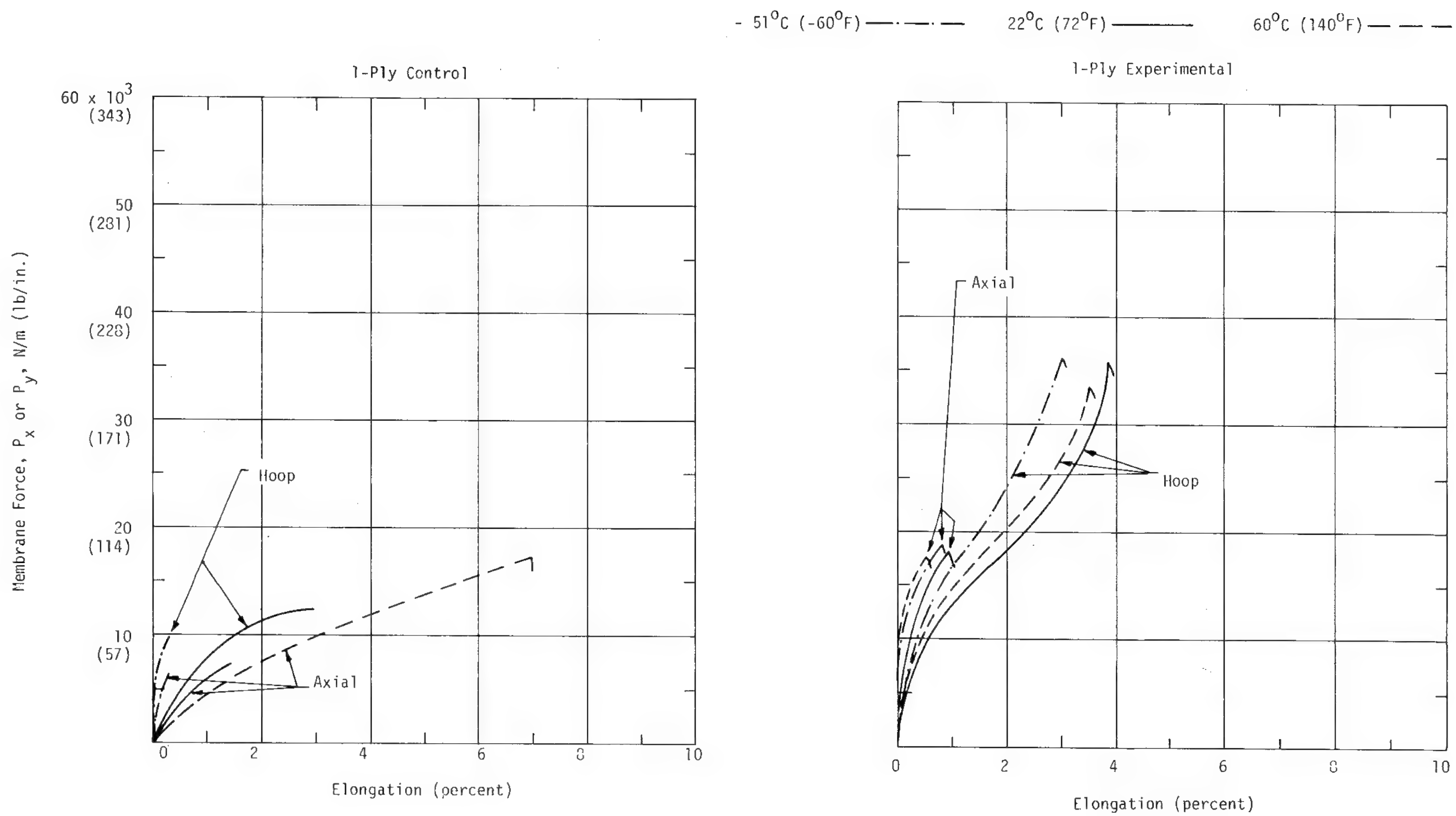


Figure 33. Stress-Strain Relations at Biaxial Stress Combination $P_x/P_y = 2$ and Zero Shear Load

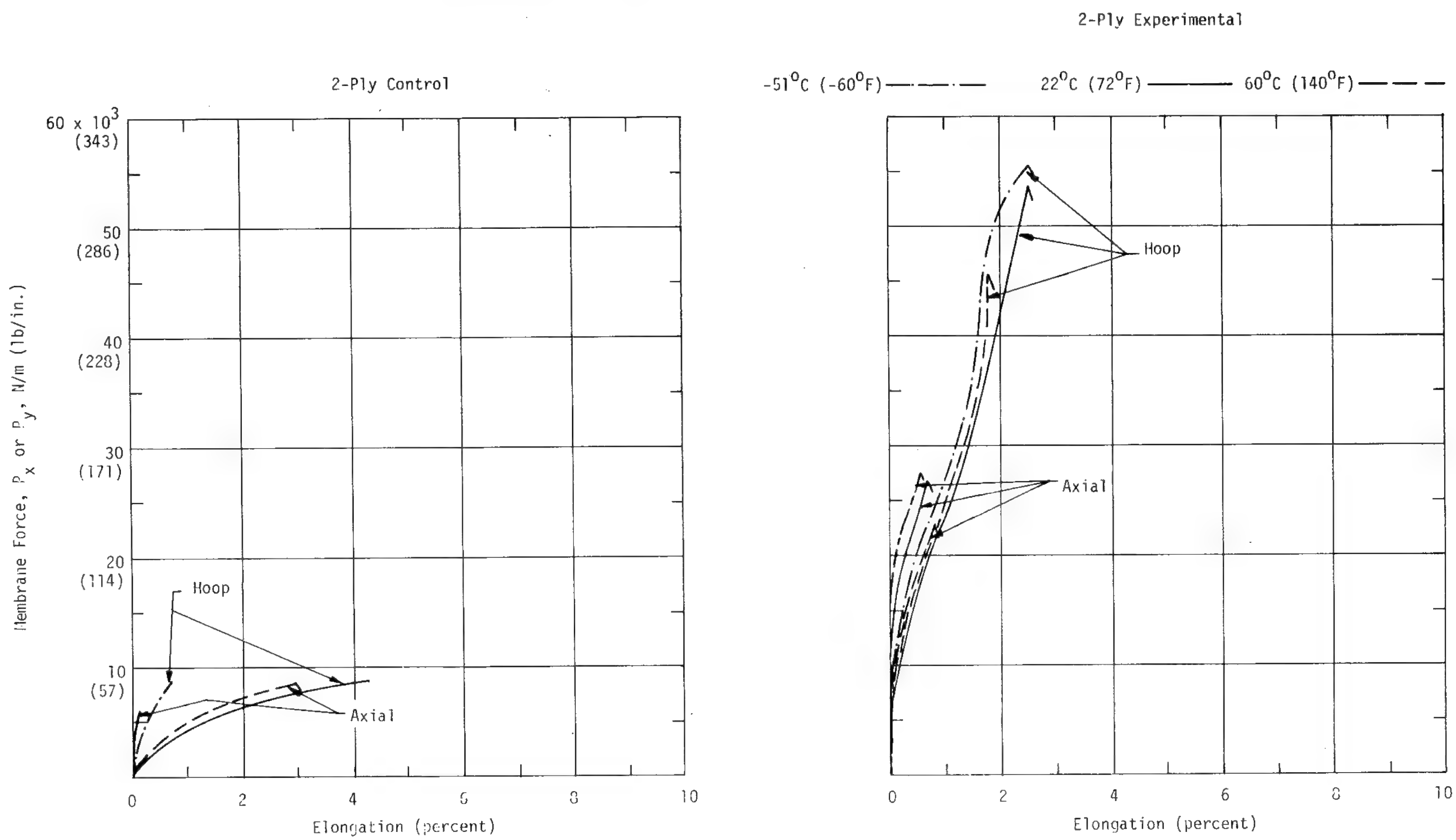


Figure 33. Stress-Strain Relations at Biaxial Stress Combination $P_x/P_y = 2$ and Zero Shear Load (Continued)

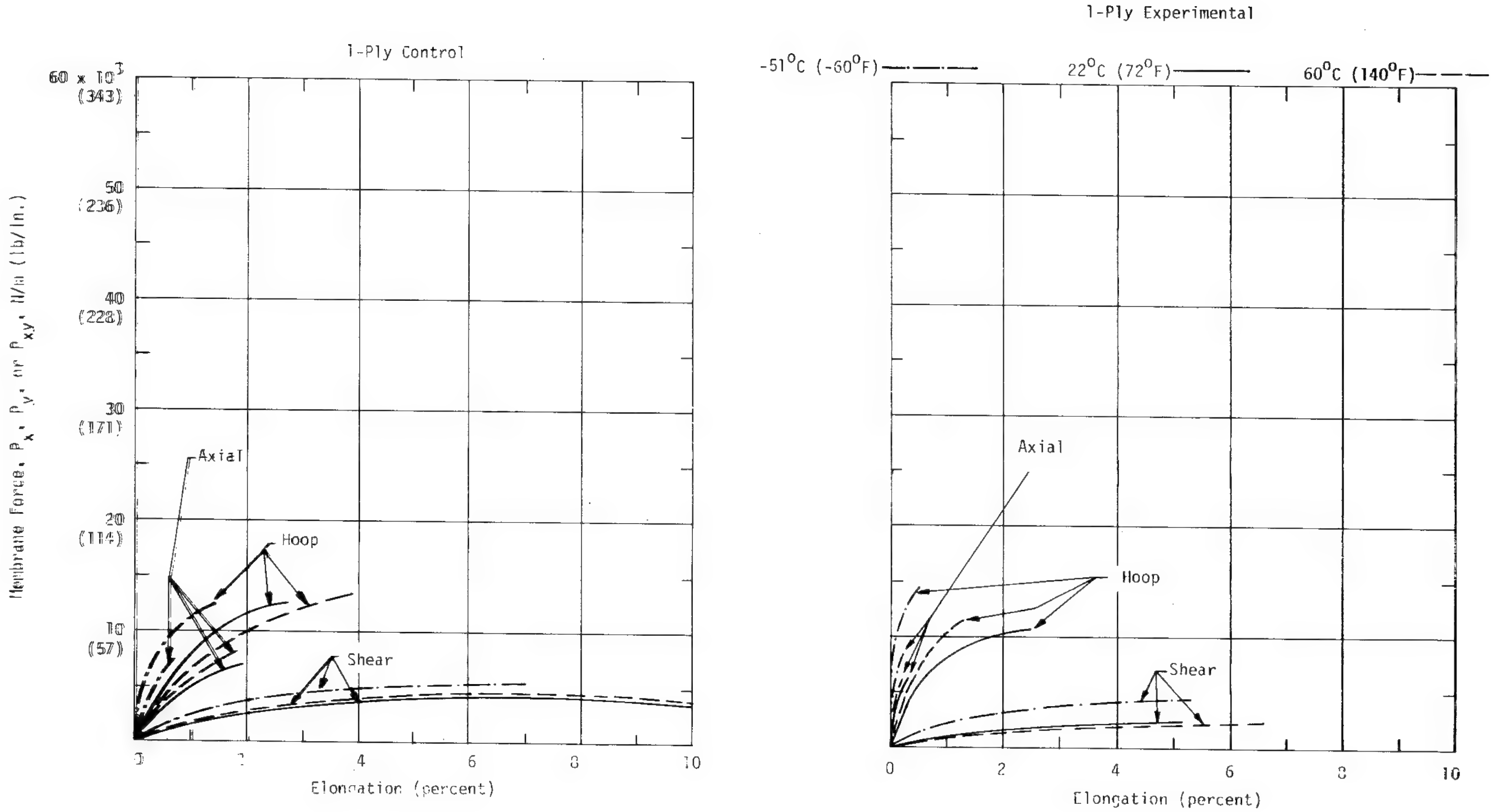


Figure 34. Stress-Strain Relations at Biaxial Stress Combination $P_x/P_y = 2$ Up to 30 Percent Ultimate Uniaxial Breaking Strength Followed by Shear Loading

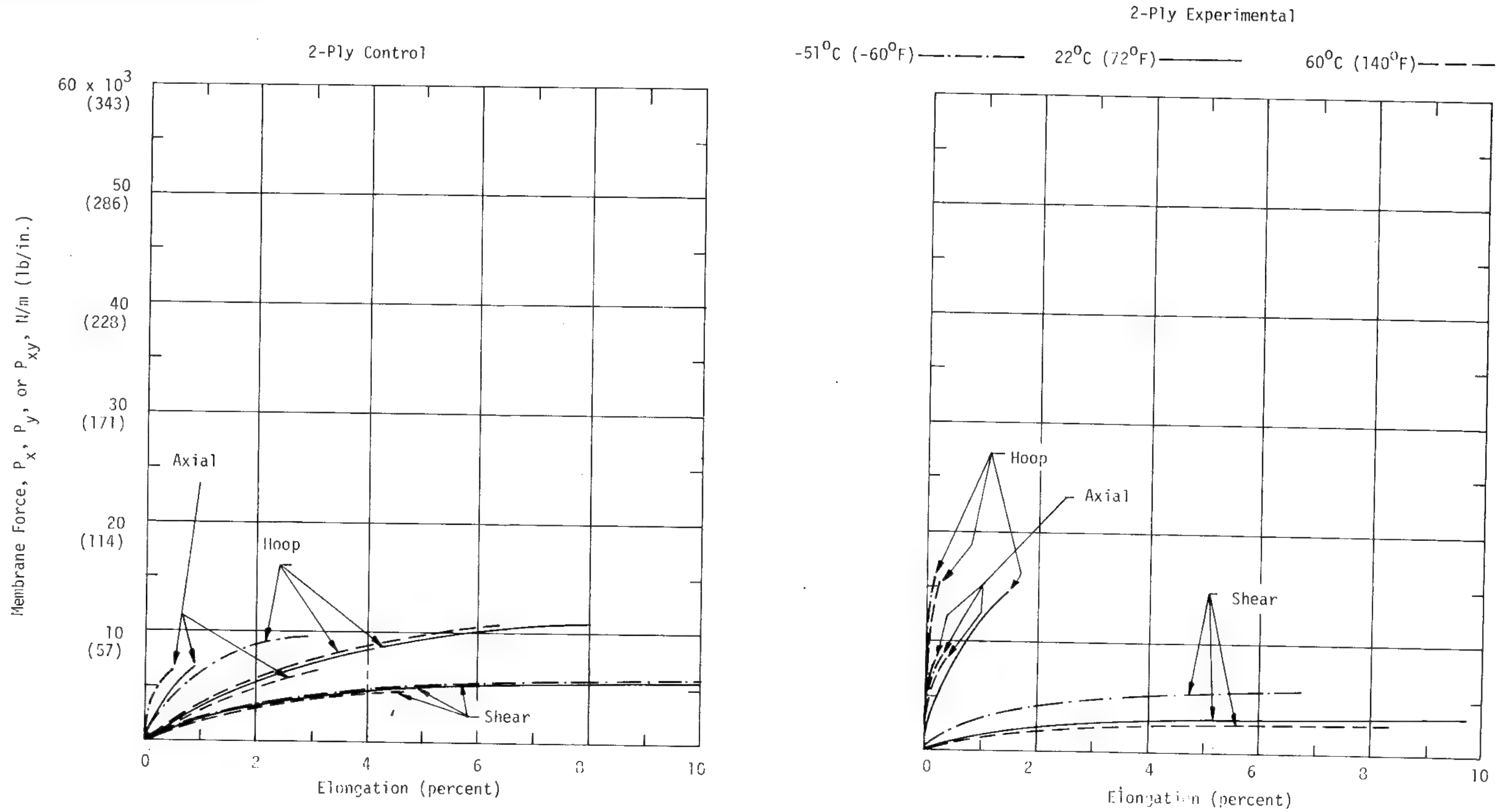


Figure 34. Stress-Strain Relations at Biaxial Stress Combination $P_x/P_y = 2$ Up to 30 Percent Ultimate Uniaxial Breaking Strength Followed by Shear Loading (Continued)

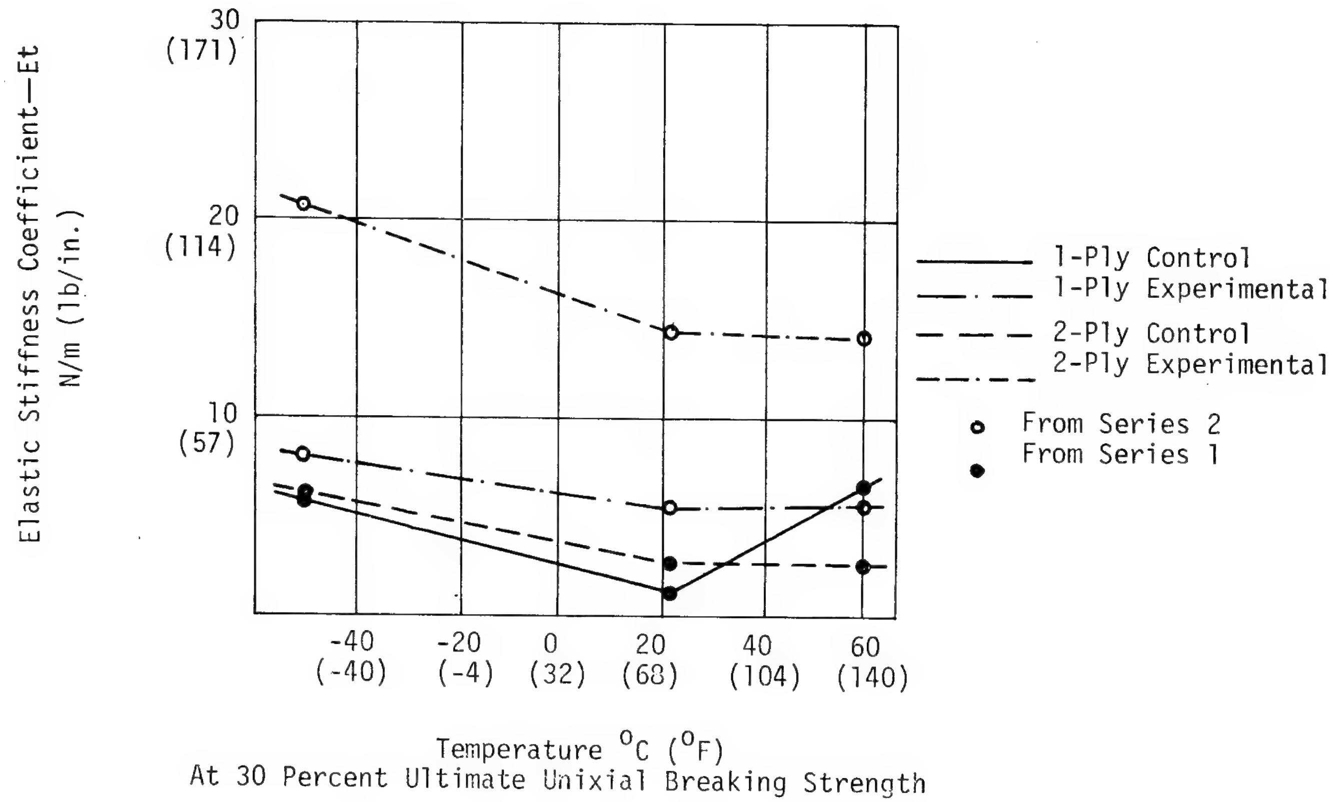


Figure 35. Effect of Temperature on Hoop (machine direction) Elastic Coefficient for Biaxial Load Combination of $P_x/P_y = 2$; $P_{xy} = 0$

Peel strength data. — The film-to-film (A and B, TABLE 3) peel strengths of control and experimental materials were fairly consistent. The addition of the adhesive wash coat reduced the peel strength of the film-fabric interface (C, TABLE 3) in about the same proportion as water immersion. The "dry" peel strength of this interface for the Kevlar experimental laminates was about two-thirds of the Dacron laminate. The wider yarn spacing in the Dacron fabric (TABLE 1-B) may account for some of the difference since the adhesive flow around the yarns would be greater than for the more tightly woven Kevlar. Interface C for Kevlar appears to be more sensitive to water than for Dacron since the addition of the wash coat to the otherwise exposed Kevlar fabric significantly reduced the effect of the water immersion.

Durability Test Results

Test data for crease effects, abrasion, blocking, tear, and flexibility relate to performance of the materials under handling, packaging, and wear in service.

Crease tests. — The crease test data presented in TABLE 4 show significant degradation of the experimental single-ply fabric strength from folding and a slight decrease in observed strength for each of the two-ply materials when compared with the data in TABLE 2. This may be caused by Kevlar having a very low elongation at failure (4 percent). This phenomena was not observed in the single-ply control material because the Dacron has a lower modulus and much larger allowable elongation to failure. For the coated two-ply fabric, the minimum attainable bend radius is several times that of the single-ply fabric. Strength loss from folding appears to be one of the shortcomings of Kevlar which could be minimized by further development. Use of a more ductile gas barrier than Mylar film or positioning the Kevlar more closely to the neutral axis of the composite to increase the effective radius of bend would decrease fold damage. Alternative weave patterns could be used to enhance the strength retained after creasing. Although crease sensitivity is an undesirable feature for inflatable materials applications, the increased strength-to-weight ratio offered by Kevlar composites may justify refined handling and packaging techniques that use mandrels and liners to control minimum bend radii.

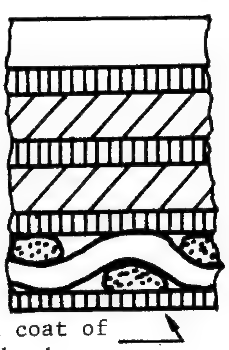
Abrasion test data. — The number of cycles required to expose the fabric by erosion of the film or coating on the outward side of the materials when abraided against themselves was:

1-Ply Control	40,000 cycles
1-Ply Experimental	69,000 cycles
2-Ply Control	21,000 cycles
2-Ply Experimental	21,000 cycles

TABLE 3

PEEL STRENGTH FOR 1-PLY LAMINATES

All data are mean values of five specimens peeled along the machine direction.

Interface (See Inset)	Control Laminate		Experimental Laminate	
	N/m	(lb/in.)	N/m	(lb/in.)
A (dry)	403	(2.3)	432	(2.5)
B (dry)	315	(1.8)	380	(2.2)
C <u>Before wash coat</u>				
(dry)	2420	(13.8)	1720	(9.8)
(wet)*	1960	(11.2)	530	(3.0)
C <u>After wash coat</u>				
(dry)	2190	(12.5)	1500	(8.6)
(wet)*	1750	(10.0)	1120	(6.4)
(A) (B) (C)  #Wash coat of adhesive	(Tedlar) (Mylar) (Mylar) (Dacron)		(Tedlar) (Mylar) (Mylar) (Kevlar)	

NOTE: *"Wet" refers to 72 hour H_2O immersion before testing

#Wash coat of adhesive was applied to fabric side as a separate operation

TABLE 4

UNIAXIAL TENSILE STRENGTH AFTER 180° CREASING

	SINGLE PLY MATERIALS				BIAS PLY MATERIALS			
	Control 1 Ply Laminate		Experimental 1 Ply Laminate		Control 2 Ply Coated		Experimental 2 Ply Coated	
	N/m	(lb/in.)	N/m	(lb/in.)	N/m	(lb/in.)	N/m	(lb/in.)
	47,950	(274)	34,650	(198)	32,550	(186)	67,200	(384)
	47,950	(274)	29,750	(170)	32,900	(188)	67,550	(386)
	47,950	(274)	36,050	(206)	29,750	(170)	67,900	(388)
	49,000	(280)	35,525	(203)	30,275	(173)	53,375	(305)
	49,700	(284)	30,450	(174)	30,275	(173)	70,350	(402)
Avg.	48,510	(277)	33,285	(190)	31,150	(178)	65,275	(373)

The superior abrasion resistance of the Tedlar film on the exterior of the laminates is primarily responsible for their greater abrasion life. Wear effects on the Tedlar were not visually evident for the first 15,000 to 20,000 cycles. The difference in abrasion life between Dacron and Kevlar fabric is probably caused by the difference in yarn size and count. Since wear begins at the points of greatest pressure, where yarns in the fabric cross, the coarse-weave Dacron concentrated the wear on a smaller area than the finer-weave Kevlar fabric.

Blocking test data. — No blocking was observed for either the control or the experimental laminate. Blocking is not expected to be a problem with materials of this type unless major changes in the adhesive or coatings are made. Since blocking forces were lower than the measurement threshold (10 mg), no quantitative results are recorded for these tests. The material samples used in the blocking tests were unlubricated (unstarched, unpowered).

To maintain control over the blocking tendency of polymeric materials, explicit curing and storage conditions are prescribed. The laminates tested were stored at 40°C (100°F) for 48 hours to cure the film-to-film bonds and for 72 hours to cure the film-to-fabric bond.

Tear test data. — Trapezoidal tear test results are presented in TABLE 5. As expected, the single-ply control exhibited the best tear resistance. The experimental single-ply fabric yielded values nearer to those of the control two-ply fabric because of the tight weave and the small yarn size which reduces the ability of the fabric to withstand the load at the tear root.

The tear resistance of the experimental two-ply fabric appears to be better than either of the experimental single-ply or the control two-ply, as may be expected, since the uniaxial tensile strength is nearly twice that of either the control or single-ply experimental materials. In general, coated materials do not provide as much tear resistance as laminated materials since open weave, higher denier fabrics with high inherent tear strength cannot be used in the former because of coating strike-through.

Except for fill direction tears in the coated fabrics, all tears occurred by progressive fracture of successive yarns in the fabric. For most of the fill direction tears in the coated material, the fabric plys separated without yarn fracture.

No criteria have been established for minimum tear resistance of tethered balloon envelopes. Standards for single wall, air-supported buildings based on a ten-year study of about 900 structures indicates the minimum trapezoidal tear resistance of a cylindrical structure, subject ot aerodynamic loading, should be directly proportional to the diameter (Reference 3). For example, the minimum trapezoidal tear strength for a 15 m (45 ft) diameter structure would be 95 n (21 lb) when operated at 250 N/m^2 (1 in. H_2O) internal pressure in winds up to 33 m/sec (65 knots).

TABLE 5

TRAPEZOIDAL TEAR TEST DATA

	SINGLE PLY MATERIALS								TWO PLY MATERIALS							
	Control				Experimental				Control				Experimental			
	Warp		Fill		Warp		Fill		Warp		Fill		Warp		Fill	
	N	(lb)	N	(lb)	N	(lb)	N	(lb)	N	(lb)	N	(lb)	N	(lb)	N	(lb)
	169	(38)	209	(47)	62	(14)	40	(9)	49	(11)	*		85	(19)	94	(21)
	169	(38)	196	(44)	58	(13)	33	(7.5)	53	(12)	*		87	(19.5)	107	(24)
	156	(35)	200	(45)	56	(12.5)	33	(7.5)	58	(13)	*		100	(22.5)	*	
	169	(38)	227	(51)	58	(13)	33	(7.5)	49	(11)	*		87	(19.5)	*	
	174	(39)	214	(48)	56	(12.5)	36	(8.0)	53	(12)	*		104	(23.5)	*	
Avg.	167	(38)	209	(47)	58	(13)	35	(7.9)	53	(12)	*		93	(21)	100	(23)

*No Tear Value -
Ply Delamination

Flex test data. — At 1000 cycles on the Bally Flexometer, the single-ply control laminate showed severe failure of the film gas barrier by cracking and delamination. At 3000 cycles, the single-ply experimental laminate began to exhibit small pinholes. At 4200 cycles, failure of the experimental laminate had proceeded to the same level as the control laminate at 1000 cycles, and both laminate specimens showed broken yarns. The two-ply coated fabrics showed delamination at about 24,000 cycles with the experimental, Kevlar material having the more extensive failure.

Since the adhesive Mylar and Tedlar films used in the lamination have from two to five times the tensile stiffness of the urethane and neoprene coatings used in the two-ply materials, the above results are not surprising. High flex life is an advantage in applications where an inflatable structure must be deflated and repackaged a large number of times or where the structure must be handled by relatively unskilled personnel.

Geometric and Mechanical Properties

Helium permeability. — Helium permeability data are presented in TABLE 6. The laminate materials had a lower permeability than the coated fabrics. Pinholes in the outer layer of coated materials allow helium to flow along yarn filaments of the fabric and through pinholes in the additional layers of coating. The two layers of Mylar film bonded with adhesive prevent lateral flow of any helium passing through one layer of film. The two-to-one ratio between permeabilities of film laminates and coated fabrics is typical for these materials. Permeability of creased or multi-cycle stressed material samples generally shows significant increases over virgin materials. Typical permeability acceptance levels for balloon materials are one to two $1/m^2/24$ hr on unstressed, uncreased material samples.

TABLE 6

HELIUM PERMEABILITY TEST DATA

($1/m^2/24$ hr at 300 N/m^2 pressure)

Single-Ply Materials		Two-Ply Materials	
Control	Experimental	Control	Experimental
0.3 - 0.5	0.3	0.5	0.4
	0.4	0.8	0.6
	0.3	0.7	0.5
Average - 0.4	0.3	0.7	0.5

Constituent weights. — Finished weights of the experimental and control composites and the breakdown of constituent weights are given in TABLE 7.

TABLE 7

ANALYSIS OF CONSTITUENT WEIGHTS

	Controls			Experimental Materials		
	Constituent	kg/m^2	(oz/yd^2)	Constituent	kg/m^2	(oz/yd^2)
Laminated Materials	Tedlar	.064	(1.89)	Tedlar	.064	(1.89)
	Adhesive	.007	(0.20)	Adhesive	.007	(0.20)
	Mylar	.008	(0.25)	Mylar	.008	(0.25)
	Adhesive	.005	(0.15)	Adhesive	.005	(0.15)
	Mylar	.008	(0.25)	Mylar	.008	(0.25)
	Adhesive	.040	(1.17)	Adhesive	.040	(1.17)
	Dacron	.129	(3.8)	Kevlar	.064	(1.89)
	Adhesive	.010	(0.29)	Adhesive	.010	(0.29)
	TOTAL	.271	(8.00)	TOTAL	.206	(6.09)
Coated Materials	Hypalon	.068	(2.0)	Hypalon	.068	(2.0)
	Urethane	.085	(2.5)	Urethane	.085	(2.5)
	Dacron	.065	(1.9)	Dacron	.048	(1.4)
	Neoprene	.119	(3.5)	Neoprene	.119	(3.5)
	Dacron	.119	(3.5)	Kevlar	.092	(2.7)
	TOTAL	.456	(13.4)	TOTAL	.412	(12.1)

To put the weight information into more meaningful terms, aerostats normally use materials in the range of 0.02 kg/m^2 (3 oz/yd^2) to 0.408 kg/m^2 (12 oz/yd^2) because of strength requirements and currently achievable strength-to-weight ratios.

Further development with Kevlar-based materials may achieve material of 0.102 kg/m^2 (3oz/yd^2) and 26,250 N/m (150 lb/in.) strength which corresponds to current materials weight 0.408 kg/m^2 (12 oz/yd^2). The two experimental materials represent the strength-to-weight improvement that was a major objective of this contractual effort. The objective for the laminated material was to reduce weight while maintaining the same strength as conventional materials, 43 kN/m (250 lb/in.) for 0.203 kg/m^2 (6 oz/yd^2). The objective for the coated materials was to achieve greater strength for conventional weight, 70 kN/m (40 lb/in.) for 0.406 kg/m^2 (12 oz/yd^2). The data in TABLE 8 indicate that these objectives have been achieved.

TABLE 8

SUMMARY OF CHARACTERISTICS OF CONTROL AND EXPERIMENTAL MATERIALS

Metric Units (English Units)

Characteristic		Control		Experimental	
		1-Ply Laminate	2-Ply Coated	1-Ply Laminate	2-Ply Coated
Weight - kg/m^2 (oz/yd^2)		0.271 (8.0)	0.456 (13.4)	0.206 (6.09)	0.412 (12.1)
Tensile Strength P_x, at 22°C (72°F) N/m (lb/in.)	$P_y/P_x = 0$	46000. (262)	32000. (184)	47000. (269)	69000. (394)
	$P_y/P_x = 2$	34000. (194)	26000. (148)	35000. (203)	54000. (308)
Tensile Strength Loss After Creasing - %		0.	3.	29.	5.
Trapezoidal Tear Strength - N (lb)	Warp	167 (38)	53 (12)	58 (13)	93 (21)
	Fill	209 (47)	Ply delamination	35 (8)	100 (23)
Abrasion Resistance - Cycles to Failure		40,000	21,000	69,000	21,000
Flex Life - Cylces to Failure		1,000	24,000	3,000	24,000
Blocking - mg		<10	<10	<10	<10
Permeability - 1/m^2/24 hr		0.4	0.7	0.3	0.5

Other Characteristics

The materials described were not analyzed for creep and relaxation effects or such thermal and electrical characteristics as absorptivity, emissivity, reflectivity, transmissibility, heat capacity, conductivity, dielectric strength, outgassing and vapor conductivity.

SUMMARY AND CONCLUDING REMARKS

Two composite, sheet materials for use in inflatable structures using fabric of the new DuPont organic fiber Kevlar have been designed, manufactured in pilot-scale quantities and tested. Two conventional materials, similar to the above, except for the use of Dacron fabric in place of Kevlar were produced and tested as experimental controls. One pair of control and experimental materials was produced by adhesive lamination of film and fabric plys. The other pair of materials was produced by coating fabrics with various elastomeric substances (TABLE 1). Laminated materials contained a single ply of square weave fabric. Coated materials each had two plys of square-weave fabric oriented at 45 degrees to each other for improved dimensional stability.

Lamination of the single ply of Kevlar fabric to film gas barriers presented no unusual difficulties. The tensile stiffness of the fabric produced a firm, stable web on process machinery.

Assembly of the coated Kevlar ply and Dacron bias ply on standard coating equipment was complicated by the difference in elasticity between the Kevlar aligned with the machine direction and the Dacron fabric tensioned on the bias. The automatic guiding equipment used to align the plys was not sufficiently sensitive to prevent fabric wrinkles which were set in place when the plys were bonded together.

The four materials were tested for tensile and shear strength, tear, abrasion, crease and flex resistance, blocking and permeability. Mean values of representative properties are given in TABLE 8.

Comparing corresponding control and experimental materials indicates the effect of replacing Dacron fabric with Kevlar. Tensile and shear break strengths were increased by about one-third for the one-ply laminates and were more than doubled for the two-ply coated materials. Tensile stiffness was increased about four-fold for one ply and five-fold for the two-ply materials.

The one-ply Kevlar laminate exhibited considerable strength loss after creasing. The coated Kevlar material was much less affected by the same treatment. Relocation of the Kevlar fabric nearer the neutral plane of the laminate would probably reduce the effect of creasing.

Trapezoidal tear strength tended to vary as the strength of individual yarns. The one-ply Dacron laminate had yarns more than twice as strong as the Kevlar yarns used in the corresponding laminate. The size of Kevlar yarn used was determined in this case by availability. For the coated fabrics, yarn size is generally determined by the allowable fabric weight and space between yarns. Any appreciable opening between yarns in a fabric to be coated allows the coating material to bleed through, which interferes with the coating operation on the reverse side. Within these constraints, tear strength can be increased by increasing the size and spacing of the yarns.

Uniaxial tensile data were obtained from coupon material specimens and data for biaxial loading with shear were obtained on cylindrical sleeve specimens, having axial seams. Biaxial tensile results were limited by difficulties encountered in testing the high strength materials. Specimen replacement and repetition of tests terminated by test peculiarities were precluded by high material and operating costs.

Maps of the biaxial specimens failure patterns are provided, indicating that the most prevalent tears were along the end clamps. The second most evident tears appear parallel to seams with more than half of these along the dummy seam; the latter are attributed to the localized stiffening and resulting discontinuities.

Test factors such as end conditions, clamps, seams, free edges, and non-uniform temperatures are considered to have an appreciable effect causing dispersions and a downward bias to both uniaxial and biaxial measured strengths.

Elastic stiffness coefficients in the warp and fill directions and for shear were obtained from load-strain curves recorded during the biaxial testing. Nonlinearities of the load-strain relations were sufficient to categorize the elastic behavior as load dependent.

From the difficulties experienced in biaxial testing it was concluded that further research is merited in biaxial testing of high strength, flexible, composite materials; particularly with respect to: improving grip mechanisms, minimizing and eliminating seams, detecting failure modes, controlling temperature environments, improving strain measurement techniques, and assessing non-uniform stress effects from radial deformations of the cylinder specimens.

The Tedlar PVF film on the laminates exhibited about twice the abrasion resistance of the elastomeric coatings on the two-ply materials. However, the coated materials' resistance to repeated flexure was about an order of magnitude better than that of the laminates. Flex life of the laminates could probably be improved by relocating the fabric near the neutral plane and by substituting a more ductile film such as Hytrel* or Saran** for the Mylar gas barrier.

Permeability levels for all materials were well within the usual limits specified for tethered aerostats. The film laminates showed about half the permeation rate of the coated materials.

The processing difficulties described do not present a serious obstacle to the manufacture of Kevlar-based composites. The bias-ply fabric could be replaced or obviated by use of a multiaxial yarn construction such as triaxially woven fabric or parallel, non-woven yarn arrays like those widely used for reinforcing polyethylene tarpaulins and vapor barriers for building construction.

The reduction in resistance to handling (creasing, flexing) from the Dacron-based materials to the Kevlar materials is attributed to the high modulus of the Kevlar fibers and to the high film moduli in the case of the laminates. Although these characteristics are undesirable for inflatable structures, the improved strength-to-weight ratios offered by Kevlar composites may justify more complex handling and packaging techniques for flexible structures incorporating Kevlar filaments.

The prime objective for the experimental laminate was to reduce weight while maintaining the same strength as in conventional counterparts. The prime objective for the experimental coated materials was to obtain greater strength for the same weight. The test program reported in this paper indicates that these objectives have been achieved.

*DuPont Registered Trademark.
**Dow CHemical Registered Trademark.

REFERENCES

1. Niccum, R.J., *Comparison of Polyester, Film-Yarn Composite, Balloon Materials Subjected to Shear and Biaxial Loading*. NASA Report CR-2047, June 1972.

2. Alley, V.L., Jr., and Faison, R.W., "Experimental Investigation of Strains in Fabric Under Biaxial and Shear Forces", *Journal of Aircraft*. Vol. A, No. 1, January 1972, pp. 55-60. American Institute of Aeronautics and Astronautics.

3. *Minimum Performance Standard for Single Wall Air-Supported Structures*. Air Structures Division, Canvas Products Association, International. March 1971.

APPENDIX A

Peel Test Methods for Laminates

1.0 Scope

1.1 This specification details a method for determining the relative resistance to delamination and/or bond strengths of laminates and tapes.

2.0 Equipment

The following equipment and apparatus are required in order to test all methods of this specification:

Instron testing machine

Rotary drum, 5" diameter x 3" wide

Hand sealing iron

Pressure sensitive double backed masking tape, 3M No. 400

Thwing-Albert 1" Precision sample cutter

Scissors

3.0 General Comments

- Peel values are not an absolute yard stick as to how well the material will serve its intended purpose.

- Peel results will vary with the type of materials being tested, their angle's of separation, adhesive thickness, speeds of separation, adhesive type, etc.

- A relatively rigid adhesive will tend to give test results that are artificially low since the stress will be concentrated in a narrow line at the point of separation. By contrast a ductile or elastic adhesive system, because it can elongate and distribute the force over a larger area, will appear much stronger in peel

- Rigid adhesives generally require a large force to initiate peel and a small force to sustain peel.

4.0 Chart Interpretation and Recording

4.1 General

Unless otherwise specified, the minimum and maximum values of each test shall be recorded on the Laboratory Request form. A minimum of 3 specimens shall be tested for each location or direction. Each

set of readings shall be totaled and averaged to provide a minimum and maximum average bond strength. Interpretation of strip chart shall be in accordance with the following instructions. Readings shall be reported in lbs/inch, unless otherwise specified.

4.2 Minimum, Average and Maximum Values

Most peels are reported as minimum bond. This can generally be described as an average of the 3 to 5 lowest points, disregarding spikes, on the chart (see Figure 1). The first ¼" and last ¼" of peel shall be excluded for purposes of obtaining the peel value.

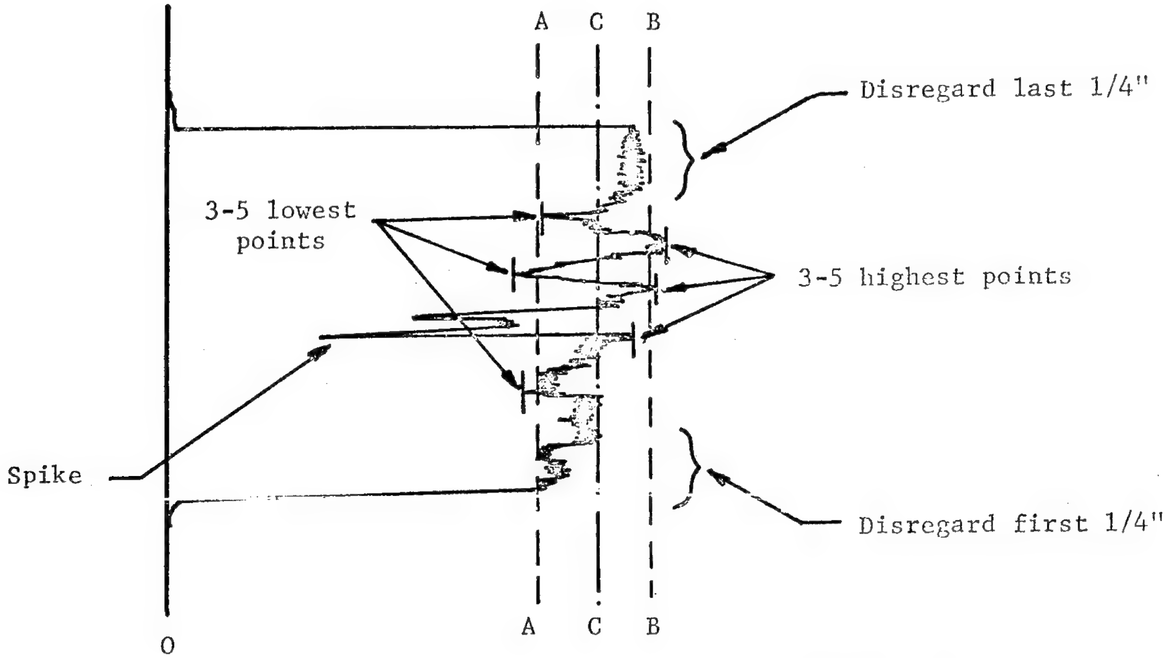


FIGURE 1

A = Minimum bond value. Note that the extreme spike is not to be included as it is not truly representative.

B = The maximum bond value (average of 3 to 5 highest points).

C = Mean value or average load value.

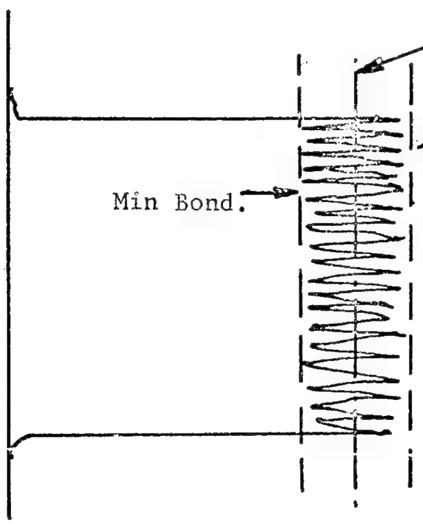
NOTE: Generally the arithmetic average of the minimum and maximum bond values should approximate the actual average load value from the chart.

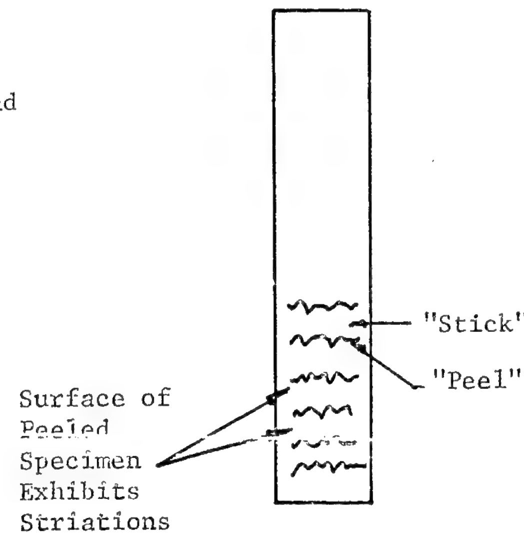
4.3 Extreme Low Values

Low extreme spikes are normally discarded unless they represent the true condition of the material. In some cases they will be representative.

4.4 Cyclic Peel

Certain adhesive systems will produce a cyclic trace on the chart like the following:





In this event, read minimum and maximum bond values for general recording purposes and identify the peel as "cyclic peel".

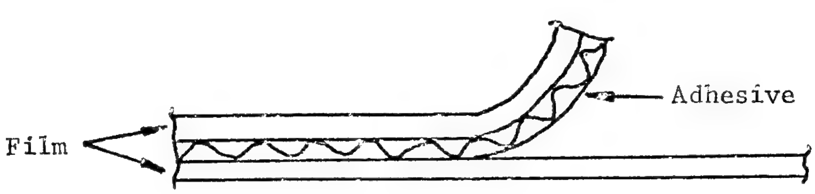
With a rigid adhesive system characterized by the above read out, it is recommended that the average load value be used because it is most representative of the true peel strength.

4.5 Failure Mode

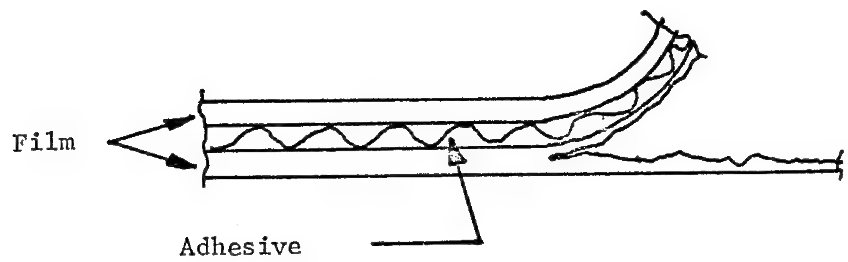
Ideally the peel test should separate the adherends by splitting the adhesive layer (cohesive failure) with part of the adhesive remaining on both substrates. In practice this seldom occurs. It is important that the failure mode be identified and recorded during peel testing.

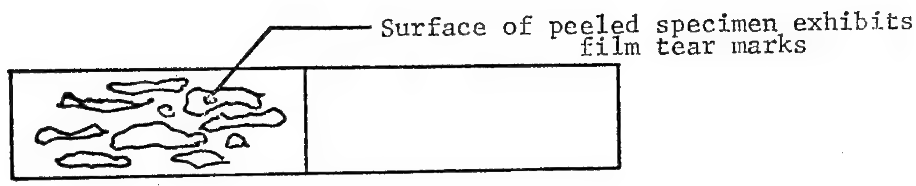
Failure modes may be one of or a combination of the following:

AF = Adhesion failure. Adhesive will stay entirely with one adherend.

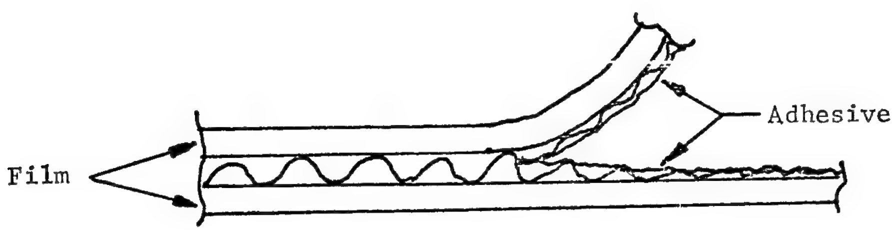


CS = Cohesive failure of substrate. Experience is required to distinguish this condition from that of adhesion failure.





CA = Cohesion failure of adhesive. Adhesive splits and leaves some adhesive on both metal foil and plastic film.



5.0 Conduct of Test

5.1 Sample Preparation

(a) Cut on Thwing-Albert precision cutter.

(b) Size - 1" x 12", to ± 0.5% accuracy.

(c) Edges must not be nicked or marred in any manner.

(d) Samples must be identified by number for each condition.

5.2 Test Procedure

(a) Separate the adherends at the end of each sample using a pair of scissors and a hot hand iron.

(b) Place a 2" wide strip of double backed pressure sensitive tape all around the drum. Fasten the drum into the lower jaw receptacle on the Instron cross head.

(c) Press one side of the specimen onto the tape and clamp the other adherend into the upper jaw.

(d) Set the Instron at the following conditions:

Crosshead travel: 2" per minute
Chart speed: 2" per minute
Full scale load switch at ten pounds

(e) Peel sample for approximately one (1) minute so that 2" of the specimen is separated.

(f) Read the minimum and maximum values from the chart and record values on the Laboratory Report Form.

APPENDIX B

Blocking Test for Laminates and Adhesive Coated Materials

1.0 Scope

This specification describes the procedures to be used when testing the blocking of laminates and adhesive coated materials.

2.0 Apparatus

2.1 Instron Testing Instrument

2.2 Controlled temperature chamber

2.3 Weights, 20 pound, 2" x 2" base

2.4 A press capable of exerting 5 psi at 130°F

3.0 Procedure

3.1 Fold a 2" x 6" sample of the laminate to be tested (adhesive side in on the first fold) twice so that a 2" x 2" square is formed. See Figure 1. This procedure may be reversed for laminates with coating on the film side.

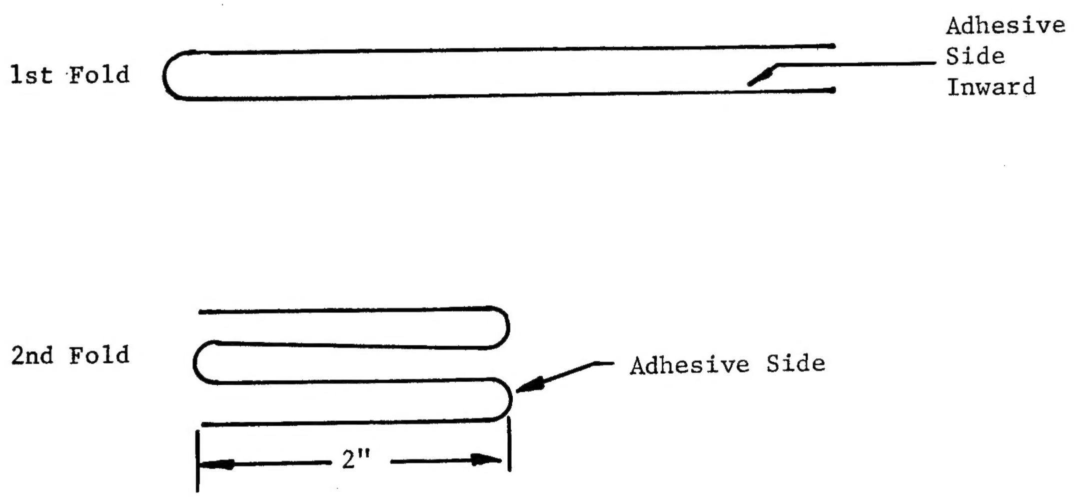


FIGURE 1

3.2 Place one weight (2.3) on the sample so that the weight covers the sample exactly. Condition one sample under weight for 24 hours at room temperature and another at 160°F.

3.3 After 24 hours, place the sample in the Instron as shown in Figure 2. Be careful not to pull the center fold open.

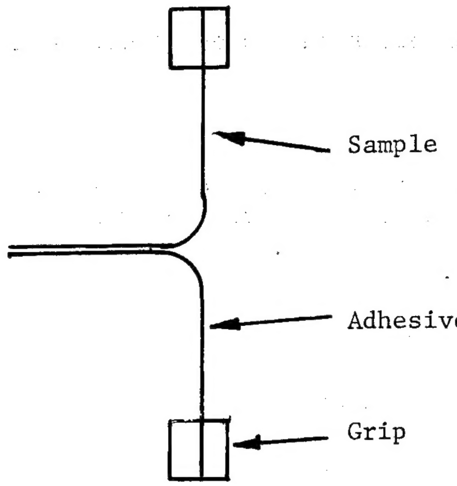


FIGURE 2

3.4 Set the Instron as follows:

Crosshead:	1.0 in/min.
Chart speed:	1.0 in/min.
Jaw spread:	2 inches

3.5 Start the crosshead and chart. Record the average peeling force on the test request form.

3.6 Acceptance Criteria for Laminates

3.6.1 For open scrim laminates failure will be described as blocking sufficient to make a hole in the film barrier.

3.6.2 For cloth laminates the maximum tolerable peel force must be specified on the test request form.

NASA-Langley, 1977 CR-2724

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